Int J Theor Phys (2010) 49: 821–834
DOI 10.1007/s10773-010-0261-1

Genesis of Dark Energy: Dark Energy as Consequence of Release and Two-Stage Tracking of Cosmological Nuclear Energy

R.C. Gupta · Anirudh Pradhan

Received: 24 November 2009 / Accepted: 20 January 2010 / Published online: 5 February 2010

Abstract Recent observations on Type-Ia supernovae and low density ($\Omega_m = 0.3$) measurement of matter including dark matter suggest that the present-day universe consists mainly of repulsive-gravity type 'exotic matter' with negative-pressure often said 'dark energy' ($\Omega_x = 0.7$). But the nature of dark energy is mysterious and its puzzling questions, such as why, how, where and when about the dark energy, are intriguing. In the present paper the authors attempt to answer these questions while making an effort to reveal the genesis of dark energy and suggest that 'the cosmological nuclear binding energy liberated during primordial nucleo-synthesis remains trapped for a long time and then is released free which manifests itself as dark energy in the universe'. It is also explained why for dark energy the parameter $w = -\frac{2}{3}$. Noting that $w = 1$ for stiff matter and $w = \frac{1}{3}$ for radiation; $w = -\frac{2}{3}$ is for dark energy because "-1" is due to 'deficiency of stiff-nuclear-matter' and that this binding energy is ultimately released as 'radiation' contributing "$+\frac{1}{3}$", making $w = -1 + \frac{1}{3} = -\frac{2}{3}$. When dark energy is released free at $Z = 80$, $w = -\frac{2}{3}$. But as on present day at $Z = 0$ when the radiation-strength-fraction (δ), has diminished to $\delta \to 0$, the $w = -1 + \delta\frac{1}{3} = -1$. This, almost solves the dark-energy mystery of negative pressure and repulsive-gravity. The proposed theory makes several estimates/predictions which agree reasonably well with the astrophysical constraints and observations. Though there are many candidate-theories, the proposed model of this paper presents an entirely new approach (cosmological nuclear energy) as a possible candidate for dark energy.

Keywords Cosmology · Dark energy · Nucleo-synthesis

R.C. Gupta
Institute of Technology (GLAITM), Mathura 281 406, India
e-mail: rcgupta@glaitm.org

A. Pradhan (✉)
Department of Mathematics, Hindu P.G. College, Zamania, 232 331, Ghazipur, UP, India
e-mail: pradhan@iucaa.ernet.in

1 Introduction

Recently observed astronomical phenomena have revolutionized the understanding of cosmology. Consequences of combined analysis of Ia Supernovae (SNe Ia) observations [1–6], galaxy cluster measurements [7] and cosmic microwave background (CMB) data [8] have shown that dark energy causing cosmic acceleration dominates the present universe. This acceleration is observed at a very small red-shift showing that it is a recent phenomenon in the late universe. Observations of 16 type Ia Supernovae made by Hubble Space Telescope (HST) [9] modified earlier astronomical results and provided conclusive evidence for deceleration prior to cosmic acceleration caused by dark energy in the recent past. The acceleration is realized with negative pressure and positive energy density that violates strong energy condition (SEC) [10–17]. This violation of SEC gives reverse gravitational effect. Due to this effect, universe gets a jerk and transition from deceleration to acceleration takes place. Phantom energy has appeared as a potential dark energy candidate in this arena, which violates both weak and strong energy conditions [18–28]. These data suggest 73% content of the universe in the form of dark energy (DE), 23% in the form of non-baryonic dark matter (DM) and the rest 4% in the form of baryonic matter as well as radiation.

It is an irony of nature and is a puzzling phenomenon that most abundant form of matter-energy in the universe is most mysterious. The simplest dark energy candidate is the cosmological constant Λ, but it needs to be extremely fine-tuned to satisfy the current value of the dark energy. Alternatively, to explain decay of the density, many dynamic models have been suggested, where Λ varies slowly with cosmic time (t) [29–31]. In addition to models with dynamic $\Lambda(t)$, many hydrodynamic models with or without dissipative pressure have been proposed in which barotropic fluid is the source of dark energy [30, 31]. Chaplygin gas as well as generalized Chaplygin gas have also been considered as possible dark energy sources due to negative pressure [28, 32–36]. Other than these approaches, some authors have considered modified gravitational action by adding a function $f(R)$ (R being the Ricci scalar curvature) to Einstein-Hilbert Lagrangian, where $f(R)$ provides a gravitational alternative for dark energy causing late-time acceleration of the universe [37–43]. A review on modified gravity as an alternative to dark energy is available in [44]. A more comprehensive review is provided in [45]. All these models are phenomenological in the sense that an idea of dark energy is introduced a priori either in term of gravitational field or non-gravitational field. In spite of these attempts, still cosmic acceleration is a challenge.

Dark energy and the accelerated expansion of the universe have been the direct prediction of the distant supernovae Ia observations which are also supported, indirectly, by the observations of the CMB anistropies, gravitational lensing and the studies of galaxy clusters. It is generally believed that the distant SNe Ia observations predict an accelerating expansion of the universe powered by some hypothetical source with negative pressure generally termed as 'dark energy'. Supernovae at relatively high red shift are found fainter than that predicted for an earlier-thought slowing-expansion and indicate that expansion of universe is actually speeding up [1–6, 46, 47]. Recent studies [47, 48] establish firmly that universe is now undergoing an acceleration; with repulsive gravity of some strange energy-form i.e., dark-energy at work. Dark energy, a 'mysterious substance' pressure of which is 'negative' and accounts for nearly 70% of total matter-energy budget of the universe, but has no clear explanation.

To understand the origin of dark energy and its nature is one of the greatest problems of the 21st century. In the present paper, a modest approach has been made to explain the genesis of dark energy, suggesting that dark energy is a result of released-free cosmological nuclear-energy in the universe; the origin of dark energy lies within the nucleus.

The out line of the paper is as follows. In Sect. 2, cosmo-dynamics of FRW model is reviewed for completeness and further use in the paper. Section 3 presents a fresh approach towards understanding the genesis of dark energy. Wherein we have suggested that the dark energy is the released binding energy during the primordial nucleo-synthesis. This dark energy decays in two stages: in constraint way as stage-1 and liberated way in stage-2. In Sect. 4, values of Ω_x at different values of Z have been estimated and are found to be well in accordance with the astrophysical constraints. In addition, theoretical estimates of deceleration parameter, with conventional and modified method, have been made in Sect. 5. After making critical discussions in Sect. 6 about the genesis of dark energy, it is noticed that the present model is in good agreement with the astrophysical constraints. Finally, conclusions are summarized in Sect. 7.

2 Cosmo-Dynamics

The standard Friedman-Robertson-Walker (FRW) cosmological model prescribes a homogeneous and an isotropic distribution for its matter in the description of the present state of the universe. The FRW equations and the analysis for cosmo-dynamics are briefly summarized as follows for clarity and completeness sake and for its subsequent uses:

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho, \tag{1}$$

$$\frac{2\ddot{a}}{a} + \left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = -8\pi G p, \tag{2}$$

where scale factor or universe-size at a particular time is $a(t)$ or simply as a. The dot denotes differentiation with respect to cosmic time t. Here, G is gravitational constant, p is pressure and ρ is the total density i.e., $\rho = \rho_r + \rho_m + \rho_x$, where subscripts r is for radiation, m is for matter (including dark matter), and x is for dark energy. The curvature factor is k and depending on k being $1, 0, -1$ the universe is closed, flat or open.

Equations (1) and (2) lead to

$$\frac{2\ddot{a}}{a} = -\frac{8\pi G}{3}(\rho + 3p). \tag{3}$$

Differentiating (1) and using (3) in it, we get

$$\dot{\rho} = -3(\rho + p)\frac{\dot{a}}{a}. \tag{4}$$

Equation (1) can be written as

$$H^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho, \tag{5}$$

where H, being Hubble constant, is defined by

$$H = \frac{\dot{a}}{a}. \tag{6}$$

Critical density ρ_c is defined as that for which the universe is flat ($k = 0$), thus (5) leads to

$$\rho_c = \frac{3H^2}{8\pi G}. \tag{7}$$

The 'question': 'whether the universe is really flat ($\rho = \rho_c$) or it is closed ($\rho > \rho_c$) or open ($\rho < \rho_c$)' needs to be revisited here. Initially it was thought (by scientists) that the universe is 'closed' and that though the universe, after the big-bang, is expanding but its expansion-rate is decelerating (due to gravity) and ultimately it was supposed to start contracting finally leading to big-crunch. However, there is a flaw in this thought, as it has been shown/stated in the literature that even if universe-density ρ is very-slightly higher than the critical density ρ_c (7), the universe should have contracted fast much-earlier than the present-age ($\approx$14 billion years) of the universe. Similarly for 'open universe', even if ρ is very-slightly lower than ρ_c, the universe would have cooled-down to death due to fast expansion at much earlier time than the present-age of the universe. The universe-age constraint limits $\rho = \rho_c$, that necessitates the 'flat' universe.

The problem (for taking $\rho = \rho_c$), however, arises if 'accounting' of matter inside the universe is made. The actual estimate of all the visible matter hardly adds up to 2% of ρ_c; if non-visible matters such as black-holes etc. are accounted for, its total come out to be, say, 4% of ρ_c. Thus there is large discrepancy to be resolved. The anomaly in galaxy-arm's rotational-speed necessiates the need of more invisible non-baryonic matter (dark-matter) which is estimated by scientists as about 23% of ρ_c. Thus the total matter is about 27%. Remaining 73% is still unaccounted for, which is called dark-energy. The dark-energy, however, has been acknowledged to have unusual property of negative (repulsive) gravity.

The recent observations and measurements that the universe is, in fact, not-decelerating but rather accelerating indicates the repulsive-gravity nature of the dark energy. Earlier, when it was thought that the universe-expansion as decelerating, the formula (8) for the 'decelerating parameter q' contained a minus-sign so to give 'q' a positive value decelerating parameter q. It may be noted that since universe is expanding (as per Hubble's observation) the first differential '$\dot{a}$' is positive; but for decelerating universe the second differentiation '$\ddot{a}$' would be negative, hence from (8) q would be positive, whereas for accelerating universe '$\ddot{a}$' is positive. The word and the formula (8) for the 'decelerating-parameter q' are, however, still 'retained', but q comes out to be negative indicating that in fact the universe expansion is actually accelerating (non-decelerating) due to dark energy.

The deceleration parameter q was defined as

$$q = -\frac{a\ddot{a}}{\dot{a}^2} = -\frac{\ddot{a}}{aH^2}. \tag{8}$$

Using the equation of state parameter w given by

$$p = w\rho, \quad \text{where } -1 \le w \le 1, \tag{9}$$

in (4), we obtain

$$\frac{\dot{\rho}}{\rho} = -3(1+w)\frac{\dot{a}}{a}, \tag{10}$$

which leads to

$$\rho \propto \frac{1}{a^{3(1+w)}}. \tag{11}$$

Equations (1) and (11), for flat universe, lead to

$$a \propto t^{\frac{2}{3(1+w)}}. \tag{12}$$

Usually, a parameter called cosmological red-shift (Z) is often referred to as a measure of the era (time t) of the universe. For example; Z_0 corresponds to the present time t_0 with present universe size (scale) a_0, and Z corresponds to some time t in the past with a smaller universe size a. In fact the cosmological red-shift for spectral-line (wavelength λ) is defined as $Z = \frac{d\lambda}{\lambda} = \frac{(a_0-a)}{a} = \frac{a_0}{a} - 1$. Thus, Z also gives a measure of universe size at a particular time, higher Z means smaller universe size in the past and is expressed as

$$\frac{a_0}{a} = 1 + Z. \tag{13}$$

Particular Cases:

(i) For $w = +1$, i.e., for stiff matter

$$\rho \propto \frac{1}{a^6} \quad \text{and} \quad a \propto t^{\frac{1}{3}}. \tag{14}$$

(ii) For $w = +\frac{1}{3}$, i.e., for radiation dominated universe

$$\rho \propto \frac{1}{a^4} \quad \text{and} \quad a \propto t^{\frac{1}{2}}. \tag{15}$$

(iii) For $w = 0$, i.e., for matter dominated (dust) universe

$$\rho \propto \frac{1}{a^3} \quad \text{and} \quad a \propto t^{\frac{2}{3}}. \tag{16}$$

(iv) For $w = -\frac{2}{3}$, i.e., for dark energy (quintessence)

$$\rho \propto \frac{1}{a} \quad \text{and} \quad a \propto t^{2}. \tag{17}$$

(v) For $w = -1$, i.e., for vacuum energy.

$$\rho = \text{constant} \quad \text{(like cosmolgical constant)}. \tag{18}$$

These variations 'ρ versus a' and 'a versus t' of the particular cases are easily obtained from (11) and (12) and are also shown in Figs. 1 and 2.

3 Nuclear Genesis of Dark Energy

3.1 Negative Pressure Due to Release of Cosmological Nuclear Energy

It is suggested that dark energy is a consequence of nuclear energy. The fusion nuclear binding energy begins to be liberated (but trapped) during primordial nucleo-synthesis; and much later ($Z = 80$) after decoupling, the nuclear binding energy is released free and appears effectively as dark energy. As shown (Fig. 3) in subsequent section of the paper; this dark

Fig. 1 Density ρ decay with space size a

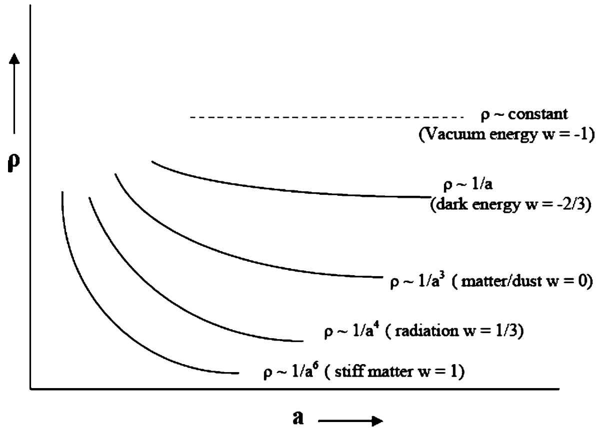
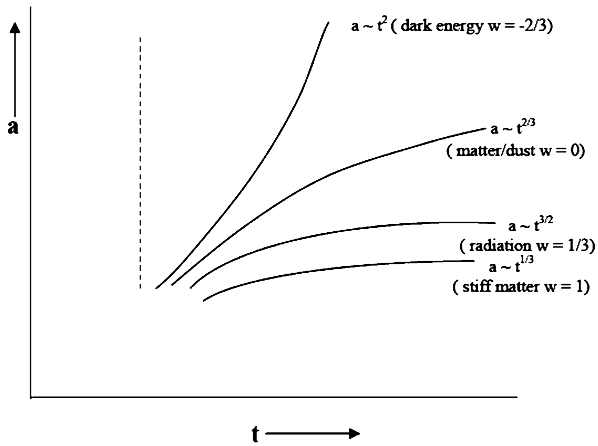


Fig. 2 Space size a expansion with time t



energy is produced earlier but released free later, of course quantity-wise ($\Omega_x = 0.0003$) insignificant; remains low during galaxy formation (say, at $Z = 3$, $\Omega_x = 0.1$), becomes 50% at transition ($Z = 0.5$, $\Omega_x = 0.5$) and emerges as dominant at present time ($Z = 0$, $\Omega_x = 0.7$), satisfying all the astrophysical constants [49].

The equation of the state parameter w for dark energy (quintessence) is taken as $w = -\frac{2}{3}$. The reason for $w = -\frac{2}{3} = -1 + \frac{1}{3}$ is explained as follows. Noting that $w = +1$ for *stiff* matter and $w = \frac{1}{3}$ for radiation; '-1' is due to 'deficiency of *stiff* (nuclear) matter' which is manifested as mass-defect (binding-energy) and '$\frac{1}{3}$' is because this released binding-energy though initially-trapped but is finally released as 'radiation'. Thus, considering that the binding-energy due to mass-defect (deficiency) in stiff-nucleus finally comes out as radiation; the equation of state parameter $w = -1 + \frac{1}{3} = -\frac{2}{3}$. When dark energy is released free at $Z = 80$, $w = -\frac{2}{3}$. But as on present day at $Z = 0$ when radiation strength has diminished to extremely-little fraction ($\delta = (1 + Z)^4/81^4$), $\delta \to 0$, the equation of state parameter comes out as $w = -1 + \delta\frac{1}{3} = -1$, that is why dark energy appears to be like the vacuum energy due to the cosmological constant Λ [29–31]. The *concept for dark-energy* that the 'deficiency of stiff-matter is effectively just opposite to the presence of stiff-matter'; is quite-analogous to the *concept in semi-conductor* that the 'deficiency (absence) of electron implies just the

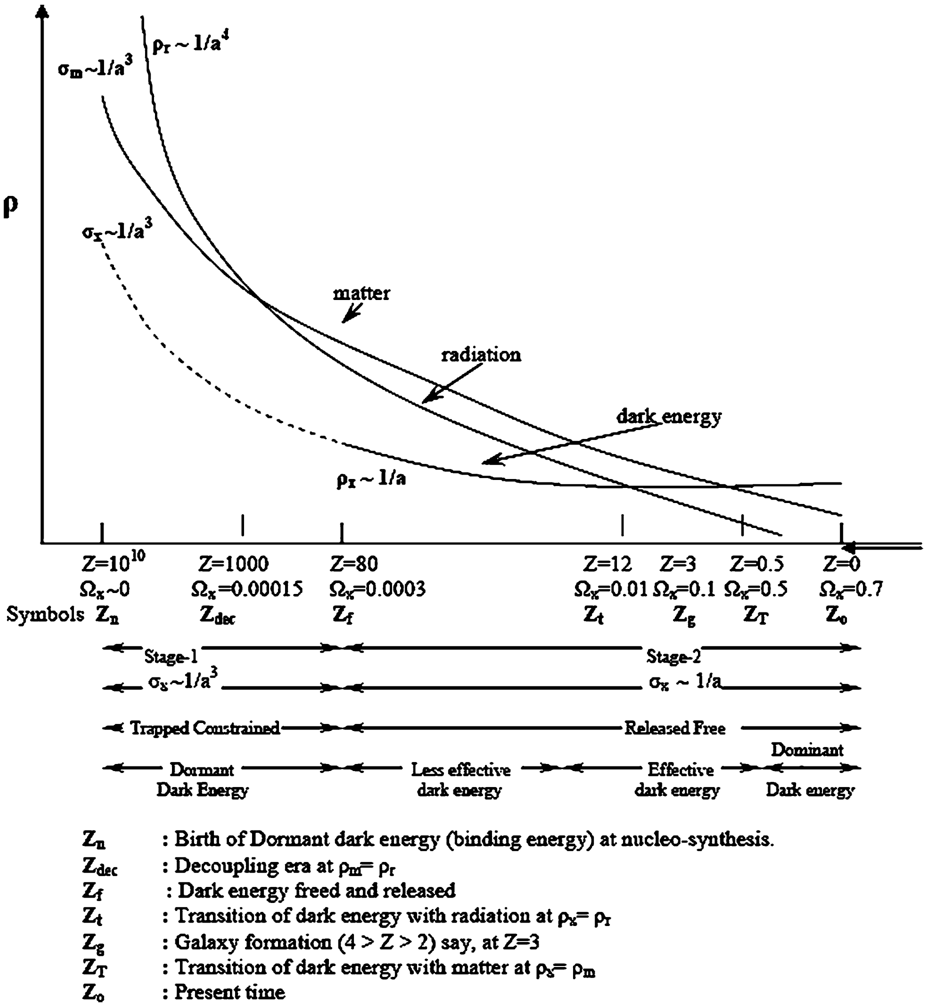


Fig. 3 Genesis of Dark Energy ρ_x and its two stage (Dominant and Free) variations/tracking along with variations of ρ_r and ρ_m

opposite of presence of electron, i.e., creation of hole'. The puzzle of negative pressure (or repulsive gravity) is, thus, almost solved; the negative pressure (or dark energy) is produced due to released-free cosmological nuclear energy.

3.2 Variation of Matter-Density and Dark-Energy-Density Much After Decoupling Era Between $Z = 80$ to $Z = 0$

Stiff-matter density decays very fast and vanishes very soon. Radiation density also decays fast and vanishes soon much after decoupling era. Although, as explained later in Sect. 3.3 and in Fig. 3, the dark energy is born much earlier in the past (nucleo-synthesis era) at about $Z = 10^{10}$ but remains trapped dormant and decays in constrained way along with the matter and is released free only after $Z = 80$ to be effective and dominant. For flat universe

($\rho = \rho_c$), the expressions for the density ratios can be written as follows

$$\rho = \rho_c = \rho_r + \rho_m + \rho_x \tag{19}$$

and

$$\Omega_c = \frac{\rho}{\rho_c}, \qquad \Omega_r = \frac{\rho_r}{\rho_c}, \qquad \Omega_m = \frac{\rho_m}{\rho_c}, \qquad \Omega_x = \frac{\rho_x}{\rho_c}. \tag{20}$$

Equations (19) and (20) lead to

$$\Omega_c = 1 = \Omega_m + \Omega_r + \Omega_x. \tag{21}$$

It is noticed that between $Z = 80$ to $Z = 0$, taking the present values of densities $\rho_{m_0} \approx 10^{-28}$ gram/cm^3, $\rho_{x_0} \approx 2 \times 10^{-28}$ gram/cm^3, $\rho_{r_0} \approx 10^{-31}$ gram/cm^3 or $\Omega_{m_0} \approx 0.3$ and $\Omega_{x_0} \approx 0.7$ and negligibly small $\Omega_{r_0} \approx 0.0003$, the variations of radiation-density, matter-density and dark-energy-density can be obtained, ratio-wise, from (15)–(17) as follows.

$$\rho_r = \frac{\rho_{r_0} a_0^4}{a^4} = 0.0003\rho_c(1+Z)^4, \tag{22}$$

$$\rho_m = \frac{\rho_{m_0} a_0^3}{a^3} = 0.3\rho_c(1+Z)^3, \tag{23}$$

$$\rho_x = \frac{\rho_{x_0} a_0}{a} = 0.7\rho_c(1+Z), \tag{24}$$

where the subscript 0 indicates the value at present time ($Z = 0$).

3.3 Genesis of Dark Energy and Its Two-Stage Tracking

Genesis of mysterious dark-energy is quite mysterious. Nevertheless, a brief schematic description of dark energy is presented here for interesting clarity. Though the decay of matter and energy (radiation-energy and dark-energy) could possibly be coupled in complex-ways, but a two-stages tracking of dark-energy as described herein (as follows) explains the past and present scenario in a reasonably good way, as it is in accordance (as shown in Sect. 4) with the astrophysical constraints [49].

Dark energy in fact is the released nuclear binding energy of cosmos. Dark energy is produced during primordial nucleo-synthesis epoch ($Z \approx 10^{10}$) in the early universe out of 'primary' matter present there, while the nucleo-synthesis (of say, Helium) liberates the binding energy as the 'seed', the seed is trapped in or around matter's lap and remains almost dormant for a long period and moves parallel to matter's foot-steps. Approximate weight of this dormant dark-energy (seed) is roughly estimated as 1% of binding energy, of 25% of primordial helium-synthesis, from 13% ($0.13 \approx \frac{0.04}{0.3}$) of baryonic-matter ($\Omega_b = 0.04$) out of total mass of (primary) matter ($\Omega_m = 0.3$); this comes out to be $\frac{\rho_x}{\rho_m} = 0.000325$ and since this era is radiation dominated era ρ_r being extremely high, gives Ω_x very close to zero. This 'seed' i.e., dark-energy (nuclear-binding-energy liberated) though has come out of matter's inside (nucleus) yet remains trapped/dormant for quite a long time at least up to decoupling era $Z = 1000$ and even beyond. When positive radiation (ρ_r) pressure is much more dominant than the negative pressure of dark energy radiation (ρ_x), the free-release of this dark energy is thus prohibited till then. While the universe is expanding, the dark energy (the seed) diminishes parallel to matter's foot-step at the same rate ($\rho \propto \frac{1}{a^3}$) from $Z = 10^{10}$ to $Z = 1000$ and even beyond $Z < 100$ up to $Z = 80$ (Fig. 3). At $Z = 80$, though dark energy Ω_x still being less than Ω_r (which opposes liberation of the trapped dark energy) but Ω_x is sufficient enough to fight with Ω_r, the dark energy is ultimately released. Thus at $Z = 80$, the dark energy (seed) is released free from matter's constrained-protection. Reason for $Z = 80$, is given in Sect. 4(v), as the meeting-point of the two-stages of the decay (tracking) of dark-energy. Then onwards ($Z < 80$) the matter density continues to decay at the same rate ($\frac{1}{a^3}$), but the dark energy (with $w = -\frac{2}{3} = -1 + \frac{1}{3}$ at release time, as explained earlier in Sect. 3.1) density decays at much slower rate ($\frac{1}{a}$) then onwards. Between $Z = 80$ to $Z = 0$, the dark energy density curve ($\rho_x \propto \frac{1}{a}$) crosses radiation density curve ($\rho_r \propto \frac{1}{a^4}$) at $Z = 12$ and crosses matter density curve ($\rho_m \propto \frac{1}{a^3}$) at $Z = 0.5$. Briefly as summary (Fig. 3): 'Dark energy is created as a result of liberated binding energy during primordial nucleo-synthesis at $Z \approx 10^{10}$ as a very small fraction ($\frac{\rho_x}{\rho_m} \approx 0.0003$, $\Omega_x \approx 0$) of total matter-mass, initially (stage-1) it remains dormant and decays fast ($\frac{1}{a^3}$) along with matter till $Z = 80$ ($\frac{\rho_x}{\rho_m} \approx 0.0003$, $\Omega_x \approx 0.0003$), and finally it is released free (stage-2) and decays slowly ($\frac{1}{a}$) between $Z = 80$ to $Z = 0$ and becomes more effective and even dominant today ($\frac{\rho_x}{\rho_m} \approx 2$, $\Omega_x \approx 0.7$).' In stage-1: Ω_x is almost equal to zero; whereas in stage-2: Ω_x increases as Z decreases; $\Omega_x = 0.0003$ at $Z = 80$; $\Omega_x = 0.01$ at $Z = 12$; $\Omega_x = 0.1$ at $Z = 3$; $\Omega_x = 0.5$ at $Z = 0.5$ and $\Omega_x = 0.7$ at $Z = 0$. The secret of dark energy hidden in nucleus comes out free and speaks aloud as '$-1 + \frac{1}{3} = -\frac{2}{3}$', and orients itself towards acceleration of the universe. Presently (as also mentioned in Sect. 3.1), due to the fast decay of radiation strength, the current value of w could be close to 'minus one'.

4 Estimation of Z and Ω_x

(i) For present time; $Z = Z_0 = 0$, $\Omega_x = 0.7$, $\Omega_m = 0.3$ (Present-day known values).

(ii) For matter/dark-energy transition ($\rho_m = \rho_x$); Z can be estimated from (23) and (24) as $Z_T = 0.5$.

(iii) For galaxy formation (say at $Z = Z_g = 3$); Ω_x can be estimated from (19)–(24) as $\Omega_{x_g} = 0.1$.

(iv) For radiation/dark-energy transition ($\rho_r = \rho_x$); Z can be estimated from (22) and (24) as $Z = Z_t = 12$.

(v) At $Z = Z_f = 80$ when dark-energy is released 'free', Ω_x can be estimated (in stage-2) from (19)–(24) as $\Omega_{x_f} = 0.0001$. The time $Z = 80$ is the joining point for stage-1 and stage-2 (Fig. 3). In stage-1, initial $\frac{\rho_x}{\rho_m} \approx 0.0003$ (see Sect. 3.3) remains constant as both ρ_x and ρ_m decay in same way ($\frac{1}{a^3}$), and for stage-2 $\frac{\rho_x}{\rho_m} \approx \frac{0.7/0.3}{(1+Z)^2}$ (see (23) and (24)); equating these $0.0003 = \frac{0.7/0.3}{(1+Z)^2}$, gives $Z \approx 80$ as the meeting point for the two stages. At the meeting point ($Z = 80$); negative pressure of dark energy is much less than positive pressure of matter and radiation energy, but appears to be strong enough so as to enable the trapped dark energy to tunnel-through to come-out as released-free.

(vi) At decoupling epoch ($\rho_m = \rho_r$) $Z = Z_{dec} = 1000$, Ω_x will be nearly half of the initial value of $\frac{\rho_x}{\rho_m}$ in stage-1 (Fig. 3), i.e., $\Omega_x = 0.00015$.

(vii) At about $Z = Z_n \approx 10^{10}$ during nucleo-synthesis era, birth of dark energy takes place. The fusion nuclear binding energy (=1%) begins to be liberated during primordial Helium synthesis (25%) from 13% ($0.13 = \frac{0.04}{0.3}$) of baryonic-matter ($\Omega_{b_0} = 0.04$) out of total matter-mass ($\Omega_{m_0} = 0.3$). Considering the liberated nuclear-binding-energy as dark-energy, the dark-energy-density is roughly estimated (1% of 25% of 13%) at 0.000325 of the total matter-density. However, since radiation density at that high

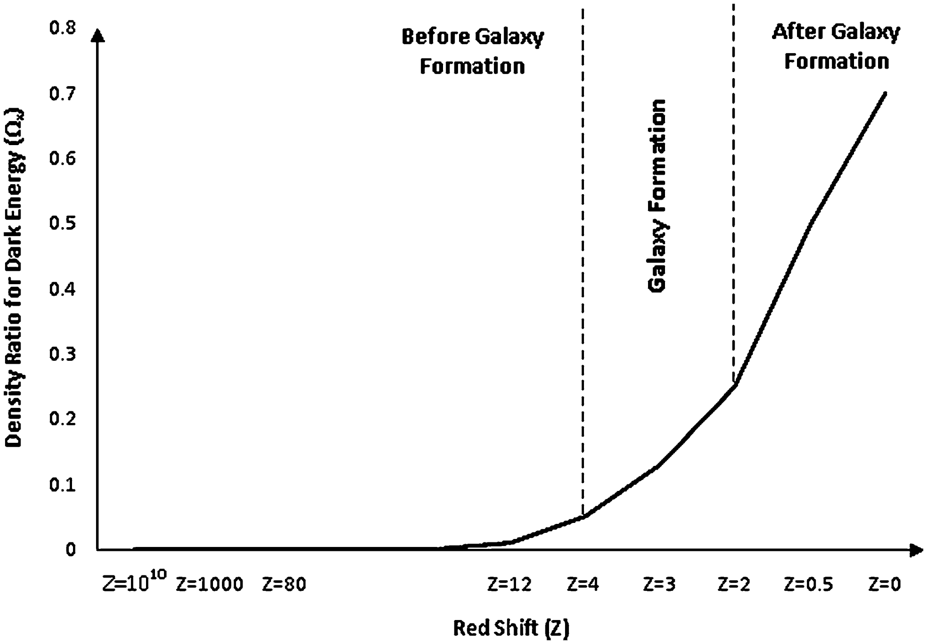


Fig. 4 Varation of density ratio for dark enery (Ω_x) verses Red shift (Z) showing that Ω_x is too low making galaxy formation feasible

value of Z (at nucleo-synthesis time $Z = Z_n \approx 10^{10}$) would be much higher than that of matter, the estimated value for Ω_{x_n} would be close-to-zero.

The liberated nuclear-energy as dark-energy, however, is trapped (as mentioned in Sect. 3.3 and in Fig. 3) in two stages. In trapped stage-1 (between $Z = 10^{10}$ to $Z = 80$) the dark-energy is trapped and dormant and varies ($\frac{1}{a^3}$) in a constrained way along with its parent matter; whereas in free stage-2 (between $Z = 80$ to $Z = 0$) the dark-energy is released free and becomes effective/dominant and varies ($\frac{1}{a}$) at slower rate during universe expansion. At $Z = 10^{10}$, $\Omega_x \approx 0$; at $Z = 80$, $\Omega_x = 0.0003$; at $Z = 12$, $\Omega_x = 0.01$; at $Z = 3$, $\Omega_x = 0.1$; at $Z = 0.5$, $\Omega_x = 0.5$ and at $Z = 0$, $\Omega_x = 0.7$. It may be noted that these estimates are quite reasonable and satisfy necessary astrophysical constraints [49]; as shown in Fig. 4, the density ratio Ω_x is initially too low and remains low till galaxy formation.

5 Estimating Deceleration-Parameter *q*

The space dimension for universe with (i) matter, (ii) dark-energy and (iii) both these combined are written as follows:

(i) For matter ($w = 0$) universe

$$a_m = a = K_m t^{\frac{2}{3}}, \quad \text{where } K_m = \frac{a_0}{t_0^{\frac{2}{3}}}. \tag{25}$$

(ii) For dark-energy ($w = -\frac{2}{3}$) universe

$$a_x = a = K_x t^2, \quad \text{where } K_x = \frac{a_0}{t_0^2}. \tag{26}$$

(iii) For the universe combined with matter (Ω_m) plus dark-energy (Ω_x)

$$a = \Omega_m a_m + \Omega_x a_x = \Omega_m K_m t^{\frac{2}{3}} + \Omega_x K_x t^2. \tag{27}$$

The deceleration-parameter ($q = -\frac{a\ddot{a}}{\dot{a}^2}$) can be estimated at present time t_0 ($\Omega_m = 0.3$, $\Omega_x = 0.7$) using (25)–(27) and is found as $q_0 = -0.52$ (as also shown in Sect. 5.2) which indicates that the expansion of the universe is accelerating. The current known value [21] is, however, $q_0 = -0.67$.

In fact, there could be following two approaches to find the deceleration-parameter which are described as follows:

5.1 Conventional Method

The 'deceleration parameter' for 'only matter' universe can easily be evaluated as $q_m = \frac{1}{2}$ and that for 'only dark-energy' universe as $q_x = \frac{1}{2} + \frac{3}{2}w$. So a simple conventional method usually followed assumes that the actual 'deceleration parameter q for the matter plus dark-energy universe' is 'weighted sum of q_m and q_x'. Thus,

$$q_0 = \frac{1}{2}\Omega_{m_0} + \left(\frac{1}{2} + \frac{3}{2}w\right)\Omega_{x_0}, \tag{28}$$

which gives for $w = -\frac{2}{3}$, $\Omega_{m_0} = 0.3$, $\Omega_{x_0} = 0.7$; $q = -0.20$ a value much different from actual known [47] value of $q_0 = -0.67$ necessitating modifications in evaluation as follows.

5.2 Modified Method

The authors suggest a modified method to evaluate the deceleration-parameter. This modified method assumes that actual 'space scale factor (a) for matter plus dark-energy universe' is 'weighted sum of a_m and a_x'. Thus, the equation for total actual space-size (a) can be written (similar to (27)) as

$$a = \Omega_m a_m + \Omega_x a_x = \Omega_m K_m t^{\frac{2}{3}} + \Omega_x K_x t^{\frac{2}{3(1+w)}}. \tag{29}$$

The deceleration parameter ($q = -\frac{a\ddot{a}}{\dot{a}^2}$) is evaluated, using (25) and (12) in (29) at present time t_0 as

$$q_0 = -\frac{[\frac{2}{9}\Omega_{m_0} - \frac{2(1+3w)}{9(1+w)^2}\Omega_{x_0}]}{[\frac{2}{3}\Omega_{m_0} + \frac{2}{3(1+w)}\Omega_{x_0}]^2}, \tag{30}$$

which gives for $w = -\frac{2}{3}$, $\Omega_{m_0} = 0.3$, $\Omega_{x_0} = 0.7$; $q_0 = -0.52$ (as found before using (27)) which is reasonably near to the known [47] observed value of $q_0 = -0.67$.

Modified (30) seems to be more correct than the conventional method's expression given by (28) since the expansion (accelerating) of the universe due to dark-energy ($a \sim t^2$) is much faster than the expansion (decelerating) of universe due to matter ($a \sim t^{\frac{2}{3}}$). This fact is taken into account in the modified-method (in (27), (29) and (30); the second term is more dominant). So, the modified method predicts more nearer to value of $q_0 = -0.52$, instead of -0.20 from conventional method, to the known observed value of -0.67.

6 Discussions

The exact time of birth $Z = 10^{10}$ or 10^9 cannot be specified very precisely. It is suggested by the authors that nuclear binding energy manifests itself as dark energy but the beginning of nuclear energy and its completion is not exactly defined/known. There is two-stage tracking (decay) of dark energy (Fig. 3). Initially in stage-1 the decay is constrained and fast during which the dark energy remains almost trapped/dormant for a long time. Finally in stage-2 the dark energy is released free at $Z = 80$ and decays slow and thus becomes more effective and dominant in due course. The free released nuclear binding energy plays its role as dark energy (with $w = -\frac{2}{3}$) creating negative-pressure or repulsive-gravity. Due to the fast decay of the radiation strength, the current value of w, however, could be $w = -1$; indicating that as if vacuum energy is dark energy. Dark energy begins with close-to-zero value of Ω_x, remains low till galaxy formation ($Z = 3$, $\Omega_x = 0.1$), becomes 50% at transition ($\Omega_x = 0.5$, $Z = 0.5$) and thereafter leads to accelerated-universe becomes dominant at present time ($Z = 0$, $\Omega_x = 0.7$). All these stand in accordance with the astrophysical constraints [49]. The dark-energy variations, in stage-2 ($\rho_x \propto \frac{1}{a}$) is governed by final/present condition (at $Z = 0$) and in stage-1 ($\rho_x \propto \frac{1}{a^3}$) is governed by initial conditions (at $Z = 10^{10}$). The meeting point for the two stages (dotted and firm curves in Fig. 3) is found at $Z = 80$. There could be some error in it ($Z = 80$) due to approximations. Though the meeting point is a point of interest in view of the fact that at this time the dark-energy is finally released-free, however, any future change in its estimate (other than $Z = 80$) will hardly have any effect on other values (estimated in Sect. 4) or on the theme and philosophy of the model which will remain unchanged.

For estimating the deceleration parameter, the authors suggest a more realistic modified-method (30) which gives an estimate of $q_0 = -0.52$ against the observed known value of $q_0 = -0.67$. The agreement is not bad. The discrepancy in the value, however, may be due to following reason: the dark energy as a result of liberation of nuclear binding energy not only takes place during primordial nucleo-synthesis ($Z = 10^{10}$ or 10^9) era but also due to fusion reaction taking place within stars after or around galaxy formation ($Z = 4$ to 0). It may be noted that only 'primordial nucleo-synthesis', which indeed is more significant, has been taken into consideration; but the 'star nucleo-synthesis' will also have some effect on acceleration of universe i.e., on the deceleration parameter in the right direction. Also, this means that nucleo-synthesis is more or less a continuous process.

Though there are many suspects (candidates) such as [50, 51] cosmological constant, vacuum energy, scalar field, brane world etc. as reported in the vast literature for the dark energy, the proposed model in this paper at least presents a new candidate (cosmological nuclear-energy) as a possible suspect (candidate) for the dark energy.

7 Conclusions

The authors propose a novel model for genesis of dark energy, indicating its origin in nucleus and suggesting that it is the released-free nuclear binding energy of cosmos which manifests itself as dark energy causing negative pressure and repulsive gravity in the universe. It explains why for dark energy $w = -\frac{2}{3}$ at release time and $w = -1$ at present time. Also, the model describes the biography of the dark energy and tells that Ω_x begins with a close-to zero value, remains low as necessary till galaxy formation say at $Z = 3$, $\Omega_x = 0.1$; transition at $Z = 0.5$, $\Omega_x = 0.5$ and becomes dominant at present time $Z = 0$, $\Omega_x = 0.7$ satisfying very well all the astrophysical constraints. The authors also propose a modified-method to estimate deceleration parameter and find that with the proposed model $q_0 = -0.52$ in reasonable agreement with known observed value. It can be metaphorically said that 'dark energy is a fossil of nuclear reaction that had taken place in the early universe and that the fossil has recently been noticed when the matter-cover over it has diminished in due course'. The secret of acceleration of big-universe is hidden in the small-nucleus.

Acknowledgements The authors thank to the Institute of Engineering and Technology (IET) and UP Technical University (UPTU), Lucknow, India for providing facility where the part of this work was done. The authors also thank Sushant Gupta for assistance in drawing the figures. The financial support (Grant No. F.6-2(29)/2008(MRP/NRCB) of University Grants Commission, New Delhi is gratefully acknowledged by A. Pradhan.

References

1. Perlmutter, S., et al.: Nature **391**, 51 (1998)
2. Perlmutter, S., et al.: Astrophys. J. **517**, 565 (1999)
3. Riess, A.G., et al.: Astron. J. **116**, 1009 (1998)
4. Tonry, J.L., et al.: Astrophys. J. **594**, 1 (2004)
5. Garnavich, P., et al.: Astrophys. J. Lett. **493**, L53 (1998)
6. Schmidt, B.P., et al.: Astrophys. J. Lett. **507**, 46 (1998)
7. Bahcall, N.A., et al.: Science **284**, 1481 (1991)
8. Spergel, D.N., et al.: Astrophys. J. Suppl. **148**, 175 (2003)
9. Riess, A.G., et al.: Astron. J. **607**, 665 (2004)
10. Ratra, B., Peebles, P.J.E.: Rev. Mod. Phys. **75**, 559 (2003)
11. Ratra, B., Peebles, P.J.E.: Phys. Rev. D **37**, 3406 (1988)
12. Frieman, J., Hill, C.T., Stebbins, A., Waga, I.: Phys. Rev. Lett. **75**, 2077 (1995)
13. Ferreira, P.G., Joyce, M.: Phys. Rev. D **58**, 023503 (1998)
14. Zlatev, I., Wang, L., Steinhardt, P.J.: Phys. Rev. Lett. **82**, 896 (1999)
15. Brax, P., Martin, J.: Phys. Rev. D **61**, 103502 (2000)
16. Sahni, V., Sami, M., Souradeep, T.: Phys. Rev. D **65**, 023518 (2002)
17. Sami, M., Dadhich, N., Shiromizu, T.: Phys. Lett. B **568**, 118 (2003)
18. Caldwell, R.R.: Phys. Lett. B **545**, 23 (2002)
19. Caldwell, R.R., Kamionkowski, M., Weinberg, N.N.: Phys. Rev. Lett. B **91**, 071301 (2003)
20. Onemli, V.K., et al.: Class. Quantum Gravity **19**, 4607 (2002)
21. Onemli, V.K., et al.: Phys. Rev. D **70**, 107301 (2004)
22. Onemli, V.K., et al.: Class. Quantum Gravity **22**, 59 (2005)
23. Sahni, V., Shtanov, Yu.V.: JCAP **0311**, 014 (2003)
24. Sahni, V.: arXiv:astro-ph/0502032
25. Johri, V.B.: Class. Quantum Gravity **19**, 5959 (2002)
26. Johri, V.B.: Phys. Rev. D **70**, 041303 (2004)
27. Johri, V.B.: Pramanna J. Phys. **59**, 1 (2002)
28. Srivastava, S.K.: Phys. Lett. B **619**, 1 (2005)
29. Overduin, J.M., Cooperstock, F.I.: Phys. Rev. D **58**, 043506 (1998)
30. Sahni, V., Starobinsky, A.: Int. J. Mod. Phys. D **9**, 373 (2000) and references therein
31. Komatsu, E., et al.: Astrophys. J. Suppl. **180**, 330 (2009)
32. Jackiw, R.: arXiv:physics/0010042
33. Bertolami, O., et al.: Mon. Not. R. Astron. Soc. **353**, 329 (2004)
34. Bento, M.C., Bertolami, O., Sen, A.A.: Phys. Rev D **66**, 043507 (2002)
35. Bilic, N., Tupper, G.B., Viollier, R.: Phys. Lett. B **535**, 17 (2002)
36. Avelino, C., Beca, L.M.G., Carvalho, J.P.M., de Martins, C.J.A.P., Pinto, P.: Phys. Rev. D **67**, 023511 (2003)
37. Capozziello, S.: Int. J. Mod. Phys. D **11**, 483 (2002)
38. Caroll, S.M., Duvvuri, V., Trodden, M., Turner, M.S.: Phys. Rev. D **70**, 043528 (2004)
39. Dolgov, A.D., Kawasaki, M.: Phys. Lett. B **573**, 1 (2003)
40. Nojiri, S., Odintsov, D.: Phys. Lett. A **19**, 627 (2004)
41. Nojiri, S., Odintsov, S.D.: Phys. Rev. D **68**, 123512 (2003)
42. Abdalaa, M.C.B., Nojiri, S., Odintsov, S.D.: Class. Quantum Gravity **22**, L35 (2005)
43. Mena, O., Santiago, J., Weller, J.: Phys. Rev. Lett. **96**, 041103 (2006)

44. Nojiri, S., Odintsov, S.D.: Int. J. Geom. Meth. Mod. Phys. **4**, 115 (2007)
45. Copeland, E.J., Sami, M., Tsujikawa, S.: Int. J. Mod. Phys. D **15**, 1753 (2006)
46. Turner, M.S.: Nucl. Phys. B (Proc. Suppl.) **72**, 69 (1999)
47. Freedman, W.L., Turner, S.S.: Rev. Mod. Phys. **75**, 1433 (2003)
48. Wang, Y., Tegmark, M.: Phys. Rev. Lett. **92**, 241302 (2004)
49. Johri, V.B.: Phys. Rev. D **63**, 103504 (2001)
50. Ostriker, J.P., Steinhardt, P.I.: Quintessentia University. Scientific American, January (2001)
51. Caldwell, R.R.: Physics web-Physics World—dark energy, May (2004)