Considering light-matter interactions in Friedmann equations

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ABSTRACT

The Friedmann equations valid for the transparent universe are modified for the universe with opacity caused by absorption of light by ambient cosmic dust in intergalactic space. The modified equations lead to a cosmological model, in which cosmic opacity produces radiation pressure that counterbalances gravitational forces. The proposed model predicts a cyclic expansion/contraction evolution of the Universe within a limited range of scale factors with no initial singularity. The maximum redshift, at which the contraction of the Universe stops, is \( z \approx 14-15 \). The model avoids dark energy and removes some other tensions of the standard cosmological model.

Subject headings: early universe – cosmic background radiation – dust, extinction – universe opacity – dark energy

1. Introduction

Dust is an important component of the interstellar and intergalactic medium, which interacts with the stellar radiation. Dust grains absorb and scatter the starlight and reemit the absorbed energy at infrared, far-infrared and microwave wavelengths (Mathis 1990; Schlegel et al. 1998; Calzetti et al. 2000; Draine 2003, 2011; Vavryčuk 2018). Since galaxies contain interstellar dust, they lose their transparency and become opaque (Calzetti 2001; Holwerda et al. 2005, 2007; Finkelman et al. 2008; Lisenfeld et al. 2008). Similarly, the Universe is not transparent but partially opaque due to ambient cosmic dust. The cosmic opacity is very low in the local Universe (Chelouche et al. 2007; Muller et al. 2008), but it might steeply increase with redshift (Ménard et al. 2010b; Xie et al. 2015; Vavryčuk 2017b).

The fact that the Universe is not transparent but partially opaque might have fundamental cosmological consequences, because the commonly accepted cosmological model was developed for the transparent universe. Neglecting cosmic opacity produced by intergalactic dust may lead to distorting the observed evolution of the luminosity density and the global stellar mass density with redshift (Vavryčuk 2017b). Non-zero cosmic opacity may invalidate the interpretation of the Type Ia supernova (SNe Ia) dimming as a result of dark energy and the accelerating expansion of the Universe (Aguirre 1999a,b; Aguirre & Haiman 2000; Ménard et al. 2010a; Vavryčuk 2019). Intergalactic dust can partly or fully produce the cosmic microwave background (CMB) (Wright 1982; Bond et al. 1991; Narlikar et al. 2003). For example, Vavryčuk (2018) showed that thermal radiation of dust is capable to explain the spectrum, intensity and temperature of the CMB including the CMB temperature/polarization anisotropies.

If cosmic opacity and light-matter interactions are considered, the Friedmann equations must be modified and the radiation pressure caused by absorption of photons by dust grains must be incorporated. Based on numerical modeling and observations of basic cosmological parameters, I show that the modified Friedmann equations avoid the initial singularity and lead to a cyclic model of the Universe with expansion/contraction epochs within a limited range of scale factors.
2. Theory

2.1. Friedmann equations for the transparent universe

The standard Friedmann equations read (Peebles 1999, p. 665)

\[
\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3} \rho - \frac{kc^2}{a^2},
\]

(1)

\[
\frac{\dot{a}}{a} = -\frac{4\pi G}{3} \left(\rho + \frac{3p}{c^2}\right),
\]

(2)

where \( a = R/R_0 = (1 + z)^{-1} \) is the relative scale factor, \( G \) is the gravitational constant, \( \rho \) is the mass density, \( k/a^2 \) is the spatial curvature of the universe, \( p \) is the pressure, and \( c \) is the speed of light. Considering the mass density \( \rho \) as a sum of matter and radiation contributions and including the vacuum contribution, we get

\[
\frac{8\pi G}{3} \rho = H_0^2 \left[ \Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda \right].
\]

(3)

Eq. (1) is then rewritten as

\[
H^2 (a) = H_0^2 \left[ \Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda + \Omega_k a^{-2} \right],
\]

(4)

with the condition

\[
\Omega_m + \Omega_r + \Omega_\Lambda + \Omega_k = 1,
\]

(5)

where \( H(a) = \dot{a}/a \) is the Hubble parameter, \( H_0 \) is the Hubble constant, and \( \Omega_m, \Omega_r, \Omega_\Lambda \) and \( \Omega_k \) are the normalized matter, radiation, vacuum and curvature terms. Assuming \( \Omega_r = 0 \) and \( \Omega_k = 0 \) in Eq. (4), we get the \( \Lambda \)CDM model

\[
H^2 (a) = H_0^2 \left[ \Omega_m a^{-3} + \Omega_\Lambda \right],
\]

(6)

which describes a flat, matter-dominated universe. The universe is transparent, because any interaction of radiation with matter is neglected. The vacuum term \( \Omega_\Lambda \) is called dark energy and it is responsible for the accelerating expansion of the Universe. The dark energy is introduced into Eqs (3-5) to fit the \( \Lambda \)CDM model with observations of the Type Ia supernova dimming.

2.2. Friedmann equations for the opaque universe

The basic drawback of the \( \Lambda \)CDM model is its assumption of transparency of the Universe and neglect of the universe opacity caused by interaction of light with intergalactic dust. Absorption of light by cosmic dust produces radiation pressure acting against the gravity, but this pressure is ignored in the \( \Lambda \)CDM model.

Let us assume a space filled by light and cosmic dust formed by uniformly distributed spherical dust grains. The dust grains absorb photons and reemit them in the form of thermal radiation. The total force produced by absorption of photons, which acts on dust in a unit volume of the Universe, is

\[
M_D \ddot{R} = S_D p_D,
\]

(7)

where \( M_D \) and \( S_D \) are the mass and surface of all dust grains in the spherical volume of radius \( R \), and \( p_D \) is the radiation pressure caused by dust absorption of the extragalactic background light (EBL) present in the cosmic space

\[
p_D = \frac{\lambda}{c} I^\text{EBL},
\]

(8)

where \( \lambda \) is the bolometric cosmic opacity (defined as attenuation per unit raypath), and \( I^\text{EBL} \) is the bolometric intensity of the EBL, which depends on redshift as (Vavryčuk 2018, his eq. 5)

\[
I^\text{EBL} = I^\text{EBL}_0 (1 + z)^4,
\]

(9)

where subscript ‘0’ means the quantity at \( z = 0 \). Since the production and absorption of photons should be in balance, the EBL intensity \( I^\text{EBL}_0 \) is related to the luminosity density \( j \) at \( z = 0 \) as (Vavryčuk 2018, his eq. 7)

\[
\lambda_0 I^\text{EBL}_0 = \frac{j_0}{4\pi}.
\]

(10)

If the comoving number density of dust grains is constant, the opacity \( \lambda \) in Eq. (8) is redshift independent, \( \lambda = \lambda_0 \) (the proper attenuation coefficient per unit ray path increases with \( z \), but the proper length of a ray decreases with \( z \)). Hence, the pressure \( p_D \) in Eq. (8) reads

\[
p_D = \frac{j_0}{4\pi c} (1 + z)^4.
\]

(11)

Inserting Eq. (11) into Eq. (7) and substituting \( R \) by the relative scale factor \( a = R/R_0 \), we obtain

\[
\ddot{a} = \frac{S_D j_0}{M_D 4\pi c a^4},
\]

(12)
where \( R_0 = 1 \). Integrating Eq. (12) in time

\[
\left( \frac{\dot{a}}{a} \right)^2 = \frac{S_D}{M_D} \frac{j_0}{6\pi c} \frac{1}{a^5},
\]

(13)

and including absorption terms defined in Eqs (12-13) into Eqs (1-2), we get a new form of the Friedmann equations valid for a model of the opaque universe

\[
\left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} \rho - \frac{S_D}{M_D} \frac{j_0}{6\pi c} \frac{1}{a^5} - \frac{k c^2}{a^2},
\]

(14)

which read for dust formed by spherical grains as

\[
\frac{\dot{a}}{a} = -\frac{4\pi G}{3} \left( \rho + \frac{3\rho_D R_D}{c^2} \right) + \frac{S_D}{M_D} \frac{j_0}{4\pi c} \frac{1}{a^5},
\]

(15)

which simplifies for a matter-dominated opaque universe (\( \Omega_r = 0 \)) as

\[
H^2(a) = H^2_0 \left[ \Omega_m a^{-3} + \Omega_a a^{-4} + \Omega_a a^{-5} + \Omega_k a^{-2} \right],
\]

(16)

which for dust formed by spherical grains are rewrite as

\[
H^2(a) = H^2_0 \left[ \Omega_m a^{-3} + \Omega_a a^{-5} + \Omega_k a^{-2} \right],
\]

(17)

with the condition

\[
\Omega_m + \Omega_a + \Omega_k = 1,
\]

(18)

where \( \Omega_m, \Omega_a \) and \( \Omega_k \) are the normalized gravity, absorption and curvature terms, respectively,

\[
\Omega_m = \frac{1}{H^2_0} \left( \frac{8\pi G \rho_0}{3} \right),
\]

(19)

\[
\Omega_a = -\frac{1}{H^2_0} \left( \frac{1}{2\pi c} \frac{j_0}{\rho_D R_D} \right),
\]

(20)

\[
\Omega_k = \frac{k c^2}{H^2_0}.
\]

(21)

The minus sign in Eq. (20) means that the radiation pressure due to absorption acts against the gravity. The dark energy is missing in Eqs (18-20), because the Type Ia supernova dimming can successfully be explained by cosmic opacity, as discussed in Vavryčuk (2019).

Eq. (19) shows that the increase of the absorption term \( \Omega_a \) with redshift is enormously high. The reasons for such a steep rise of \( \Omega_a \) with \( z \) are, however, straightforward. The steep rise combines the three following effects: (1) the increase of photon density with \((1 + z)^3\) due to the space contraction, (2) the increase of absorption of photons with \((1 + z)\) due to the shorter distance between dust grains, and (3) the increase of rate of absorbed photons by dust grains with \((1 + z)\) due to time dilation.

2.3. Distance-redshift relation

The scale factor \( a \) of the Universe with the zero expansion rate is defined by the zero Hubble parameter in Eq. (19), which yields a cubic equation in \( a \)

\[
\Omega_k a^3 + \Omega_m a^2 + \Omega_a = 0.
\]

(22)

Taking into account that \( \Omega_m > 0 \) and \( \Omega_k < 0 \), Eq. (22) has two distinct real positive roots for

\[
\left( \frac{\Omega_m}{3} \right)^2 > \left( \frac{\Omega_k}{2} \right)^2 |\Omega_a| \quad \text{and} \quad \Omega_k < 0.
\]

(23)

Negative \( \Omega_a \) and \( \Omega_k \) imply that

\[
\Omega_m > 1 \quad \text{and} \quad \rho_0 > \rho_c = \frac{8\pi G}{3H^2_0}.
\]

(24)

Under these conditions, Eq. (19) describes a universe with a cyclic expansion/contraction history and the two real positive roots \( a_{\min} \) and \( a_{\max} \) define the minimum and maximum scale factors of the Universe. For \( \Omega_a \ll 1 \), the scale factors \( a_{\min} \) and \( a_{\max} \) read approximately

\[
a_{\min} \cong \sqrt{\frac{\Omega_a}{\Omega_m}} \quad \text{and} \quad a_{\max} \cong \frac{\Omega_m}{\Omega_k},
\]

(25)

and the maximum redshift is

\[
z_{\max} = \frac{1}{a_{\min}} - 1.
\]

(26)

The scale factors \( a \) of the Universe with the maximum expansion/contraction rates are defined by

\[
\frac{da}{da} H^2(a) = 0,
\]

(27)
which yields a cubic equation in $a$
\[2\Omega_b a^3 + 3\Omega_m a^2 + 5\Omega_a = 0. \quad (30)\]

Taking into account Eq. (17) and Eqs (21-23), the deceleration of the expansion reads
\[\ddot{a} = -\frac{1}{2} H_0^2 \left[\Omega_m a^{-2} + 3\Omega_a a^{-4}\right]. \quad (31)\]

Hence, the zero deceleration is for the scale factor
\[a = \sqrt{\frac{3\Omega_a}{\Omega_m}}. \quad (32)\]

Finally, the comoving distance as a function of redshift is expressed from Eq. (19) as follows
\[dr = \frac{c}{H_0} \frac{dz}{\sqrt{\Omega_m (1 + z)^3 + \Omega_a (1 + z)^5 + \Omega_k (1 + z)^2}}. \quad (33)\]

3. Modeling

3.1. Parameters for modeling

For calculating the expansion history and cosmic dynamics of the Universe, we need observations of intergalactic dust grains, the galaxy luminosity density, the mean mass density, and the expansion rate and curvature of the Universe at the present time.

The size $a$ of dust grains is in the range of $0.01 - 0.2 \mu m$ with a power-law distribution $a^{-q}$ with $q = 3.5$ [Mathis et al. 1977, Jones et al. 1996], but silicate and carbonaceous grains dominating the scattering are typically with $a \approx 0.1 \mu m$ [Draine & Fraise 2009, Draine 2011]. The grains of size $0.07 \mu m \leq a \leq 0.2 \mu m$ are also ejected to the IGM most effectively [Davies et al. 1998, Bianchi & Ferrara 2005]. The grains form complicate fluffy aggregates, which are often elongated or needle-shaped [Wright 1982, 1987]. Considering that the density of carbonaceous material is $\rho \approx 2.2 g cm^{-3}$, and the silicate density is $\rho \approx 3.8 g cm^{-3}$ [Draine 2011], the average density of porous dust grains is $\approx 2 g cm^{-3}$ or less [Flynn 1994, Kocifaj et al. 1999, Kohout et al. 2014].

The galaxy luminosity density is determined from the Schechter function [Schechter 1976], It has been measured by large surveys 2dFGRS [Cross et al. 2001], SDSS [Blanton et al. 2001], 2003] or CS [Brown et al. 2001]. The luminosity function in the R-band was estimated at $z = 0$ to be $(1.84 \pm 0.04) \times 10^8 hL_\odot Mpc^{-3}$ for the SDSS data [Blanton et al. 2003] and $(1.9 \pm 0.6) \times 10^8 hL_\odot Mpc^{-3}$ for the CS data [Brown et al. 2001]. The bolometric luminosity density is estimated by considering the spectral energy distribution (SED) of galaxies averaged over different galaxy types, being thus $1.4 - 2.0$ times larger than that in the R-band (Vavryčuk 2017b, his table 2): $j = 2.5 - 3.8 \times 10^8 hL_\odot Mpc^{-3}$.

The Hubble constant $H_0$ is measured by methods based on the Sunyaev-Zel’dovich effect [Birkinshaw 1999, Bonamente et al. 2006] or gravitational lensing [Suyu et al. 2013, Bouvin et al. 2017], gravitational waves [Vitale & Chen 2018, Howlett & Davis 2020] or acoustic peaks in the CMB spectrum provided by Planck Collaboration et al. (2016), and they yield values mostly ranging between 66 and 74 km s$^{-1}$ Mpc$^{-1}$. Here I use an estimate $H_0 = 69.8 \pm 2.5$ km s$^{-1}$ Mpc$^{-1}$ of $H_0$ obtained by Freedman et al. (2019) using the SNe Ia with a red giant branch calibration.

Assuming the ΛCDM model, the CMB and BAO observations indicate a nearly flat Universe (Planck Collaboration et al. 2016). This method is not, however, model independent and ignores an impact of cosmic dust on the CMB. A model-independent method proposed by Clarkson et al. (2007) is based on reconstructing the comoving distances by Hubble parameter data and comparing with the luminosity distances [Li et al. 2016, Wei & Wu 2017] or the angular diameter distances [Yu & Wang 2016]. The cosmic curvature can also be constrained using strongly gravitational lensed SNe Ia [Qi et al. 2019] and using lensing time delays and gravitational waves [Liao 2019]. The authors report the curvature term $\Omega_k$ ranging between -0.3 to 0 indicating a closed universe, not significantly departing from flat geometry.

3.2. Results

Estimating the required cosmological parameters from observations (see Table 1), I calculate the upper and lower limits of the volume of the Universe and the evolution of the Hubble parameter with time. The mass density of the Universe higher than the critical density is considered, and subsequently $\Omega_m$ is higher than 1. The Hubble constant is $H_0 = 69.8$ km s$^{-1}$ Mpc$^{-1}$,
Table 1: Maximum redshift and scale factor in the cyclic model of the opaque universe

| Model | ε  | $c_{S/M}$ | $j_0$ ($10^8 h L_\odot Mpc^{-3}$) | $\Omega_m$ | $\Omega_a$ | $\Omega_k$ | $a_{\text{max}}$ | $z_{\text{max}}$ |
|-------|----|-----------|---------------------------------|-------------|-------------|-------------|----------------|----------------|
| A     | 20 | 4.0       | 3.8                             | 1.2         | $-7.2 \times 10^{-3}$ | -0.192 | 6.2 | 11.8 |
| B     | 5  | 1.9       | 2.5                             | 1.2         | $-2.3 \times 10^{-3}$ | -0.198 | 6.1 | 21.8 |
| C     | 15 | 3.3       | 3.1                             | 1.2         | $-4.8 \times 10^{-3}$ | -0.195 | 6.1 | 14.7 |
| D     | 15 | 3.3       | 3.1                             | 1.1         | $-4.8 \times 10^{-3}$ | -0.095 | 11.6 | 14.1 |
| E     | 15 | 3.3       | 3.1                             | 1.3         | $-4.8 \times 10^{-3}$ | -0.295 | 4.4 | 15.3 |

Parameter $\epsilon$ is the ratio of the major to minor axis of the prolate spheroidal dust grains, $c_{S/M}$ is the correction for the S/M ratio of the spheroidal to spherical dust grains, $j_0$ is the bolometric luminosity density at $z = 0$, $\Omega_m$, $\Omega_a$, and $\Omega_k$ are the matter, absorption and curvature terms, and $a_{\text{max}}$ and $z_{\text{max}}$ are the maximum scale factor and redshift, respectively. Models A, B and C predict low, high and optimum values of $z_{\text{max}}$. Models E, D and C predict low, high and optimum values of $a_{\text{max}}$.

Fig. 1.— Maximum redshift as a function of $\Omega_m$ and $\Omega_a$. 

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Fig. 2.— The evolution of the Hubble parameter with redshift in the past and with the scale factor in the future (in km s$^{-1}$ Mpc$^{-1}$). (a) The blue dashed, dotted and solid lines show Models A, B and C in Tab. 2. (b) The blue solid, dashed, and dotted lines show Models C, D and E in Tab. 2. The black dotted lines mark the predicted maximum redshifts (a) and maximum scale factors (b) for the models considered. The black dot denotes the state in C when the deceleration of the expansion is zero. The dot is not at the maximum of $H(z)$ because the zero deceleration is with respect to time but not with respect to $z$. The red solid line shows the flat ΛCDM model with $H_0 = 69.8$ km s$^{-1}$ Mpc$^{-1}$, taken from Freedman et al. (2019), and with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

Fig. 3.— Comoving distance as a function of redshift $z$. The blue dashed, dotted and solid lines show Models A, B and C in Tab. 2. The black dotted lines mark the predicted maximum redshifts for the models considered. The red solid line shows the flat ΛCDM model with $H_0 = 69.8$ km s$^{-1}$ Mpc$^{-1}$, taken from Freedman et al. (2019), and with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. 
taken from Freedman et al. (2019). The dust grains are assumed to be prolate spheroids with a varying shape ratio. The specific dust density is 2000 kg m\(^{-3}\). Parameter \(\Omega_a\) varies from \(-7.6 \times 10^{-3}\) to \(-2.5 \times 10^{-3}\) depending on the luminosity density \(j_0\) and the spheroidal shape of the dust grains (see Eq. (22) and Table 1).

As seen in Fig. 1, the maximum redshift of the Universe depends mostly on \(\Omega_a\), and ranges from 11.5 to 21.3. The maximum redshift \(z_{\text{max}}\) calculated approximately by Eqs (26-27) has an accuracy higher than 1% compared to the exact solution of Eq. (24). In contrast to \(\Omega_{\text{min}}\) depending mostly on \(\Omega_a\), the maximum scale factor \(a_{\text{max}}\) of the Universe depends primarily on \(\Omega_m\). The limiting value is \(\Omega_m = 1\), when \(a_{\text{max}}\) is infinite. For \(\Omega_m = 1.1, 1.2, 1.3\) and 1.5, the scale factor \(a_{\text{max}}\) is 11.6, 6.5, 4.4 and 3.0, respectively.

The history of the Hubble parameter \(H(z)\) and its evolution in the future \(H(a)\) calculated by Eq. (19) is shown in Fig. 2 for five scenarios summarized in Table 1. As mentioned, the form of \(H(z)\) is controlled by \(\Omega_a\) (Fig. 2), while the form of \(H(a)\) is controlled by \(\Omega_m\) (Fig. 2b). The Hubble parameter \(H(z)\) increases with redshift up to its maximum. After that the function rapidly decreases to zero. The drop of \(H(z)\) is due to a fast increase of light attenuation producing strong repulsive forces at high redshift. For future epochs, function \(H(a)\) is predicted to monotonously decrease to zero. The rate of decrease is controlled just by gravitational forces; the repulsive forces originating in light attenuation are negligible. For a comparison, Fig. 2 (red line) shows the Hubble parameter \(H(a)\) for the standard ΛCDM model (Planck Collaboration et al. 2016), which is described by Eq. (6) with \(\Omega_m = 0.3\) and \(\Omega_\Lambda = 0.7\). The deceleration of the expansion becomes zero before \(H(z)\) attains its maximum (see the black dot in Fig. 2b). The redshift of the zero deceleration is about 2/3 of the maximum achievable redshift.

The distance-redshift relation for the proposed cyclic model of the Universe is quite different from the standard ΛCDM model (see Fig. 3). In both models, the comoving distance monotonously increases with redshift, but the redshift can go possibly to 1000 or more in the standard model, while the maximum redshift is likely 14-15 in the cyclic model. The increase of distance with redshift is remarkably steeper for the ΛCDM model than for the cyclic model. The ratio between distances in the cyclic and ΛCDM models is about 0.54.

4. Other supporting evidence

The cyclic cosmological model of the opaque universe successfully removes some tensions of the standard ΛCDM model:

- The model does not limit the age of stars in the Universe. For example, observations of a nearby star HD 140283 (Bond et al. 2013) with age of 14.46±0.31 Gyr are in conflict with the age of the Universe, 13.80 ± 0.02 Gyr, determined from the interpretation of the CMB as relic radiation of the Big Bang (Planck Collaboration et al. 2016).

- The model predicts the existence of very old mature galaxies at high redshifts. The existence of mature galaxies in the early Universe was confirmed, for example, by Watson et al. (2015) who analyzed observations of the Atacama Large Millimetre Array (ALMA) and revealed a galaxy at \(z > 7\) highly evolved with a large stellar mass and heavily enriched in dust. Similarly, Laporte et al. (2017) analyzed a galaxy at \(z \approx 8\) with a stellar mass of \(\approx 2 \times 10^8 M_\odot\) and a dust mass of \(\approx 6 \times 10^6 M_\odot\). A large amount of dust is reported by Venemans et al. (2017) for a quasar at \(z = 7.5\) in the interstellar medium of its host galaxy. In addition, a remarkably bright galaxy at \(z \approx 11\) was found by Oesch et al. (2016) and a significant increase in the number of galaxies for \(5.5 < z < 12\) was reported by Ellis et al. (2013). Note that the number of papers reporting discoveries of galaxies at \(z \approx 10\) or higher is growing rapidly (Hashimoto et al. 2018; Hoag et al. 2018; Oesch et al. 2018; Salmon et al. 2018).

- The model is capable to explain the SNe Ia dimming discovered by Riess et al. (1998) and Perlmutter et al. (1999) without introducing dark energy as the hypothetical energy of vacuum (Vavryčuk 2019), which is difficult to explain under the quantum field theory (Weinberg et al. 2013). Moreover, the speed of gravitational waves and the speed
of light differ for most of dark energy models \cite{Sakstein2017,Ezquiaga2017}, but observations of the binary neutron star merger GW170817 and its electromagnetic counterparts proved that both speeds coincide with a high accuracy.

- The model avoids a puzzle, how the CMB as relic radiation could survive the whole history of the Universe without any distortion \cite{Vavrycuk2017} and why several unexpected features at large angular scales such as non-Gaussianity \cite{Vielva2004,Cruz2005,PlanckCollaboration2014} and a violation of statistical isotropy and scale invariance are observed in the CMB.

5. Discussion and conclusions

The radiation pressure as a cosmological force acting against the gravity has not been proposed yet, even though its role is well known in the stellar dynamics \cite{Kippenhahn2012}. The radiation pressure is important in the evolution of massive stars \cite{Zinnecker2007}, in supernovae stellar winds and in galactic wind dynamics \cite{Aguirre1999,Aguirre2000,Aguirre1999b}. Apparently, the radiation pressure in the evolution of the Universe was overlooked, because the Universe was assumed to be transparent. By contrast, the role of radiation pressure is essential in the opaque universe model, because it is produced by absorption of photons by cosmic dust. Since the cosmic opacity and the intensity of the EBL steeply rise with redshift, the radiation pressure, negligible at present, becomes significant at high redshifts and can fully eliminate gravity and stop the universe contraction.

Hence, the expansion/contraction evolution of the Universe might be a result of imbalance of gravitational forces and radiation pressure. Since the comoving global stellar and dust masses are basically independent of time with minor fluctuations only, the evolution of the Universe is stationary. Obviously, the recycling processes of stars and galaxies \cite{Segers2016,Angles-Alcazar2017} play a more important role in this model than in the standard cosmology.

The age of the Universe in the cyclic model is unconstrained and galaxies can be observed at any redshift less than the maximum redshift $z_{\text{max}}$. The only limitation is high cosmic opacity, which can prevent observations of the most distant galaxies. Hypothetically, it is possible to observe galaxies from the previous cycle/cycles, if their distance is higher than that corresponding to $z_{\text{max}} \approx 14 - 15$. The identification of galaxies from the previous cycles will be, however, difficult, because their redshift will be a periodic function with increasing distance.

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