A cosmological model with negative energy photons*

Qin Yi-Ping(覃一平)†

Center for Astrophysics, Guangzhou University, Guangzhou 510006, *China*
Physics Department, Guangxi University, Nanning 530004, *China*

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According to recent investigations of states of quantum fields, we postulate that there exist negative energy photons in the universe. With this assumption, we find a solution of Einstein's equation without introducing the cosmological constant. A new and sizable type Ia supernovae sample is employed to perform a fit with our model and the conventional model. Both models can well account for the current type Ia supernovae observation and they are not distinguishable. With the new model, the cause of the accelerated expansion of the universe and the mechanism of the negative pressure existing in outer space can be explained in ordinary physical terms.

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PACC: 9880D, 9880L

1. Introduction

One of the greatest scientific achievements obtained in the past decade is the observation of type Ia supernovae (SNe Ia) which could serve as cosmological candles.[1,2] It was found that a flat cosmological model with a positive cosmological constant can well explain the observation. The cosmological constant is often referred to as the vacuum energy produced by the phase transitions that the universe undergoes as it cools. However, there are some points against this scenario.[3] For instance, the amount of vacuum energy produced by all the phase transitions could be about 10^{120} times greater than the density of all the matter in the universe.[4]

States of quantum fields which involve negative energy densities have been produced in the laboratory, including the experiments of the Casimir force[5] and squeezed states of light.[6] Visser and Barcelo[7] pointed out that quantum effects can violate all the energy conditions of general relativity. Thus, efforts of searching for classical systems, field theories that are quite natural in terms of quantum field theory, which violate the energy conditions, have become reasonable.[8,9] Since the strong energy condition is violated by current observations, it is concluded that no possible combination of 'normal' matter is capable of fitting the observation data.[10]

Based on these facts, we abandon in this paper the cosmological constant but introduce abnormal matter, and then explore a solution of Einstein's equation and check if the solution can account for the SNe Ia data.

2. The model

Our analysis is based on the framework of the Friedmann–Robertson–Walker (FRW) cosmology. We call a vacuum not losing any energy a 'normal vacuum' and that losing some a 'deficit vacuum'. According to quantum electrodynamics, normal vacuums are full of all kinds of electromagnetic modes. Thus, if there ever exist deficit vacuums in the universe, it would be more reasonable to assume them acting as negative energy photons rather than negative energy matter.

We postulate that there exist negative energy photons in the universe. Taking into account the contribution of negative energy photons, we assign

$$\rho = \rho_{\rm pos} + \rho_{\rm neg}, \qquad (\rho_{\rm pos} \geq 0, \quad \rho_{\rm neg} \leq 0) \tag{1}$$

and

$$p = p_{\rm pos} + p_{\rm neg}, \tag{2}$$

where 'pos' denotes positive energy and 'neg' represents negative energy.

The flat nature of the universe was confirmed by recent observations.[11,12] In the following we consider only the model of a flat universe, i.e., $k = 0$. In this space–time, Einstein's equation produces (in units of $c = 1$)[13]

$$3\ddot{R} = -4\pi G(\rho + 3p)R, \tag{3}$$

$$R\ddot{R} + 2\dot{R}^2 = 4\pi G(\rho - p)R^2, \tag{4}$$

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†Corresponding author. E-mail: ypqin@126.com
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and the conservation equation of the energy–momentum tensor gives rise to

$$\dot{p}R^3 = \frac{\mathrm{d}}{\mathrm{d}t}[R^3(\rho + p)], \tag{5}$$

where $\dot{R} \equiv \mathrm{d}R/\mathrm{d}t$.

Equation (5) can be written as

$$R\dot{\rho} = -3(\rho + p)\dot{R}. \tag{6}$$

From Eqs. (3) and (4) one can obtain

$$\dot{R}^2 = \frac{8\pi G}{3}\rho R^2. \tag{7}$$

This indicates $\rho \geq 0$. Cosmological observations have suggested and confirmed that the universe is expanding. Thus $\dot{R} > 0$ and it leads to

$$\rho > 0. \tag{8}$$

Since $\dot{R} > 0$, Eq. (7) could give rise to

$$\dot{R} = \sqrt{\frac{8\pi G\rho}{3}}R. \tag{9}$$

Combining Eqs. (6) and (9) one finds

$$\dot{\rho} = -\sqrt{24\pi G\rho}(\rho + p). \tag{10}$$

Define

$$\eta \equiv -\frac{\rho_{\mathrm{neg}}}{\rho}. \tag{11}$$

Then we obtain

$$\rho_{\mathrm{pos}} = (1 + \eta)\rho. \tag{12}$$

It is clear that $\eta \geq 0$ (as $\rho_{\mathrm{neg}} \leq 0$ and $\rho > 0$) and $\rho_{\mathrm{pos}} \geq \rho$.

For negative energy photons, we assume that

$$p_{\mathrm{neg}} = \frac{\rho_{\mathrm{neg}}}{3}. \tag{13}$$

Thus

$$p = p_{\mathrm{pos}} - \frac{\eta}{3(1 + \eta)}\rho_{\mathrm{pos}}. \tag{14}$$

Within the distance where SNe Ia are observable, positive energy of the universe must be dominated by particles rather than photons. Then the pressure of positive energy matter must be negligible compared with the mass density of the matter, that is $p_{\mathrm{pos}} \ll \rho_{\mathrm{pos}}$ (in the following we will see that η is not very small). Therefore, the term p_{pos} would be negligible in Eq. (14). It then leads to

$$p = -\frac{\eta}{3}\rho. \tag{15}$$

Inserting Eq. (15) into Eq. (10) we obtain

$$\dot{\rho} = -\sqrt{24\pi G}\left(1 - \frac{\eta}{3}\right)\rho^{3/2}. \tag{16}$$

In the late epoch of the universe, it makes sense that $\dot{\rho} \leq 0$. Therefore we find the following restriction:

$$0 \leq \eta < 3 \tag{17}$$

(according to the analysis below, $\eta = 3$ could be ruled out). At the late epoch of the universe, the total amount of positive or negative energy would remain unchanged. Then the density ratio of the two kinds of energy would be unchanged (as the universe expands, both ρ_{pos} and ρ_{neg} would decline at the same rate). We therefore assume that η is a constant at the late epoch of the universe. In this situation, Eq. (16) can be integrated. The solution is

$$\rho = \left[\sqrt{6\pi G}\left(1 - \frac{\eta}{3}\right)(t + C_1)\right]^{-2}, \tag{18}$$

where C_1 is the integral constant. Inserting Eq. (18) into Eq. (9) and then integrating the latter we obtain

$$R = C_2\left[\sqrt{6\pi G}\left(1 - \frac{\eta}{3}\right)(t + C_1)\right]^{2/(3-\eta)}, \tag{19}$$

where C_2 is another integral constant. From Eq. (19) one finds that $\eta = 3$ corresponds to $R = 0$ which is not true in our universe.

In the space–time of the R–W metric with $k = 0$, the luminosity distance of an object with redshift z can be determined by

$$D_{\mathrm{L}} = (1 + z)R_0\int_t^{t_0}\frac{\mathrm{d}t}{R}, \tag{20}$$

where t_0 is the present time and R_0 is the present value of the cosmic scale factor. Applying Eq. (19) we obtain from Eq. (20) that

$$D_{\mathrm{L}} = \begin{cases} (t_0 + C_1)\dfrac{3 - \eta}{1 - \eta}[1 + z - (1 + z)^{(1+\eta)/2}], & (\eta \neq 1), \\ (t_0 + C_1)(1 + z)\ln(1 + z), & (\eta = 1), \end{cases} \tag{21}$$

where the well-known relation $R_0/R = 1+z$ is applied.

Following the conventional definitions of Hubble's constant H_0 and the deceleration parameter q_0, which refer to the present moment t_0,[13] let us define

$$H \equiv \frac{\dot{R}}{R} \tag{22}$$

and

$$q \equiv -\frac{R\ddot{R}}{\dot{R}^2} \tag{23}$$

as the Hubble constant and the deceleration parameter referring to any given moment t. Obviously, $H(t_0) = H_0$ and $q(t_0) = q_0$. With Eqs. (9), (18) and (19) we obtain from Eq. (22) that

$$H = \frac{2}{(3-\eta)(t+C_1)}. \tag{24}$$

Thus

$$H_0 = \frac{2}{(3-\eta)(t_0+C_1)}. \tag{25}$$

Applying Eqs. (3), (7) and (15), one obtains from Eq. (23) that

$$q = \frac{1-\eta}{2}. \tag{26}$$

(The restriction $0 \leq \eta < 3$ leads to $-1 < q \leq 1/2$.) Equation (25) gives

$$t_0 + C_1 = \frac{1}{(1+q)H_0}. \tag{27}$$

The luminosity distance then can be expressed as

$$D_{\rm L} = \begin{cases} \dfrac{1}{H_0}[1+z-(1+z)^{1-q}]/q, & (q \neq 0), \\ \dfrac{1}{H_0}(1+z)\ln(1+z), & (q=0), \end{cases} \tag{28}$$

It is plain that $\eta = 0$ corresponds to $q = 1/2$. In this situation, $D_{\rm L} = 2(1+z-\sqrt{1+z})/H_0$, which is the well-known solution of the flat cosmological model without the cosmological constant.

3. Application to type Ia supernovae

Compiled and employed in Ref. [14] are 185 SNe Ia, where the number of the 'gold' and 'silver' sources is 155. A recent sample of SNe Ia can be found in Ref. [15], where 21 new SNe Ia sources are presented. We get from them 176 'gold' and 'silver' SNe Ia (sample 1). Provided in this sample are the well measured distance moduli and redshifts of the sources. The moduli have been derived according to $\mu = m - M = 5\log d_{\rm L} + 25$, where m is the apparent magnitude, M is the absolute magnitude, $d_{\rm L}$ is the luminosity distance in units of megaparsecs.

We perform a fit to sample 1 with Eq. (28), and for a comparison, we perform a fit to the same sample with the conventional FRW flat cosmological model as well. It has been shown that the cosmological parameters $\Omega_{\rm M}$ and Ω_Λ are independent of the value for the Hubble constant.[1] We thus fix the constant and take $H_0 = 65$ km·s^{-1}·Mpc^{-1}. The best fit for our model gives $q = -0.30$ ($\sigma_- = 0.51$, $\sigma_+ = 0.53$) and $\chi^2_{\rm dof} = 1.33$, and for the conventional flat FRW model the fit yields $\Omega_{\rm M} = 0.31$ ($\sigma_- = 0.24$, $\sigma_+ = 0.41$) (where $\Omega_\Lambda = 1 - \Omega_{\rm M}$) and $\chi^2_{\rm dof} = 1.31$. Displayed in Fig. 1 are the fitting results. The two fitting curves almost entirely overlap and they all well pass through the 'central region' of the adopted data. The results indicate that both models can well account for the current SNe Ia observation.

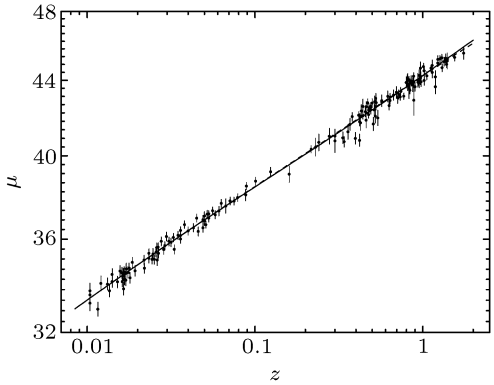


Fig. 1. Plot of distance modulus vs redshift ($\mu - z$) for the fits to the data of the 176 'gold' and 'silver' SNe Ia sources (sample 1). The filled circles represent the observation data, the solid line is the fit with Eq. (28) (where $q = -0.30$), and the dash line is the fit with the conventional flat FRW model (where $\Omega_{\rm M} = 0.31$, $\Omega_\Lambda = 0.69$). Note that the two fitting curves (the solid and dash lines) almost entirely overlap.

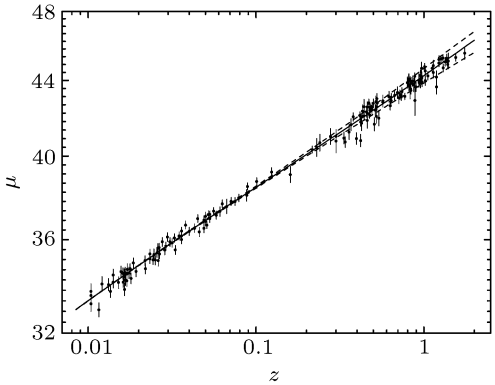


Fig. 2. Plot of distance modulus vs. redshift ($\mu - z$) for the fits to the data of the 176 'gold' and 'silver' SNe Ia sources (sample 1). The upper dash line is the curve of the conventional flat FRW model with $\Omega_{\rm M} = 0.31 - 0.24$, and the lower dash line is that with $\Omega_M = 0.31 + 0.41$. Other symbols are the same as they are in Fig. 1.

The '1σ fitting region' confined by the curves of the conventional flat FRW model with $\Omega_{\rm M} = 0.31 - \sigma_-$ and $\Omega_{\rm M} = 0.31 + \sigma_+$ respectively are shown in Fig. 2. The fitting curve of Eq. (28) is well inside the region. (Considering the '1σ fitting region' confined by the curves of Eq. (28) with $q = -0.30 - \sigma_-$ and $q = -0.30 + \sigma_+$ respectively produces a similar plot.) It reveals that, with the current SNe Ia data, the two models are not distinguishable.

4. Energy conditions

The pointwise energy conditions of general relativity include the null energy condition (NEC), weak energy condition (WEC), strong energy condition (SEC), and dominant energy condition (DEC).[16−18] The formulas are simple in the FRW space–time:[10]

$$\text{NEC} \Leftrightarrow (\rho + p \geq 0), \tag{29}$$

$$\text{WEC} \Leftrightarrow (\rho \geq 0) \quad \text{and} \quad (\rho + p \geq 0), \tag{30}$$

$$\text{SEC} \Leftrightarrow (\rho + 3p \geq 0) \quad \text{and} \quad (\rho + p \geq 0), \tag{31}$$

$$\text{DEC} \Leftrightarrow (\rho \geq 0) \quad \text{and} \quad (\rho \pm p \geq 0). \tag{32}$$

According to the so-called Quantum Interest Conjecture,[19] negative energy in one place and time will always be compensated by positive energy elsewhere. The general form of our model strictly follows this principle (see inequality (8)).

After fitting the SNe Ia data we get $q = -0.30$ ($\eta = 1.60$). Finally we find in our model: $\rho > 0$, $p = -(1.60/3)\rho < 0$, $\rho - p = (4.60/3)\rho > 0$, $\rho + p = (1.40/3)\rho > 0$, $\rho + 3p = -0.60\rho < 0$. This shows that SEC is violated while other energy conditions are not.

5. Discussion

Unlike the conventional model, the new model clearly suggests that the cause of the accelerated expansion of the universe comes from the negative pressure associated with negative energy photons (which leads to $\rho + 3p < 0$, and then to $\ddot{R} > 0$). As negative energy photons possess negative energy, a collision from the photon would yield a certain amount of the opposite momentum for an ordinary object. Thus, random collisions from the photons would give a result of undergoing negative pressure for ordinary objects.

Although how energy of some vacuums in our universe has been lost is beyond the scope of this paper, we still want to remind the reader that the universe was very compact during its birth. Could it be possible that some electromagnetic modes of some vacuums were 'originally' lost? We are wondering if it is possible that the Casimir force might somehow do some work at some spots of space–time and then might leave behind some vacuums where energy has been lost.

Due to recent investigations,[20] we would like to know if the intrinsic distribution of standard candles such as SNe Ia would play a role in estimating the parameters of our model. We hope that this will be explored in the near future. The observational constraint on the accelerating universe in the framework of a 5D bounce cosmological model is also an interesting issue studied recently.[21] If there exist negative energy photons in our universe, how would the observational constraint on the accelerating universe be affected? A model of quintessential inflation with radiation and matter has been found to be a good match for the current astronomical observation.[22] We are wondering how the dynamics of quintessential inflation would be influenced when negative energy photons are taken into account.

Particle tunnelling radiation from black holes has been widely discussed in recent years.[23−29] It is known that the phenomenon of Hawking radiation is associated with the event of negative energy particles being created inside a black hole. Is it possible that some negative energy photons are created at spots very close to the horizon and then might stand outside the black hole due to fluctuation? We long to see research on this issue in the near future.

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