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Sandage–Loeb test for the new agegraphic and Ricci dark energy models

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ABSTRACT

The Sandage–Loeb (SL) test is a unique method to explore dark energy at the "redshift desert" ($2 \lesssim z \lesssim 5$), an era not covered by any other dark energy probes, by directly measuring the temporal variation of the redshift of quasar (QSO) Lyman-α absorption lines. In this Letter, we study the prospects for constraining the new agegraphic dark energy (NADE) model and the Ricci dark energy (RDE) model with the SL test. We show that, assuming only a ten-year survey, the SL test can constrain these two models with high significance.

1. Introduction

The astronomical observations of type Ia supernovae (SNIa) indicate that our universe is undergoing an accelerating expansion [1]. This cosmic acceleration has also been confirmed by other observations, such as the large scale structure (LSS) [2] and the cosmic microwave background (CMB) [3]. Nowadays it is the most accepted idea that a mysterious dominant component, dark energy, with large enough negative pressure, is responsible for this cosmic acceleration. Among all theoretical models, the preferred one is the so-called ΛCDM model, which consists of a mixture of Einstein's cosmological constant Λ and the cold dark matter (CDM). The ΛCDM model provides an excellent explanation for the acceleration of the universe and the existing observational data. However, the cosmological constant has to face severe theoretical problems such as the puzzle why the dark energy density today is so small compared to typical particle scales. Therefore, except the ΛCDM model, many dynamical dark energy models have been proposed, in which the equation of state (EoS) of dark energy is no longer a constant but slightly evolves with time. For reviews of dark energy, see, e.g., Ref. [4].

In the face of so many candidate models, it is extremely important to identify which one is the correct model by using the observational data. The measurement of the expansion rate of the universe at different redshifts is crucial to discriminate these competing candidate models. Up to now, a number of cosmological tools have been used to successfully probe the expansion and the geometry of the universe. These, typically, include the luminosity distance of SNIa, the position of acoustic peaks in the CMB angular power spectrum, and the scale of baryon acoustic oscillations (BAO) in the power spectrum of matter extracted from galaxy catalogues. Recently, the application of time evolution of cosmological redshift as a test of dark energy models has become attractive, since this method opens a new window of exploring the "redshift desert" ($2 \lesssim z \lesssim 5$). In addition to being a direct probe of the dynamics of the expansion, this method has the advantage of not relying on a determination of the absolute luminosity of the observed sources, but only on the identification of stable spectral lines, so this method can reduce the uncertainties from systematic or evolutionary effects.

Sandage [5] was the first to propose the possible application of this kind of observation as a cosmological tool. However, owing to the tininess of the expected variation, this observation was deemed impossible at that time. In 1998, Loeb [6] revisited this suggestion and argued that the redshift variation of quasar (QSO) Lyman-α absorption lines could be detected in the not too distant future, given the advancement in technology occurred over the last forty years. In fact, the cosmological redshift variation at 1σ would be detected in a few decades, if a sample of a few hundred QSOs could be observed with high resolution spectroscopy with a ten meter telescope. This method is usually referred to as "Sandage–Loeb" (SL) test. The possibility of detecting the temporal variation of redshift with the Cosmic Dynamics Experiment (CODEX) was first analyzed by Corasaniti, Huterer and Melchiorri [7]. Their work [7] has provided the first quantitative analysis of the SL test, from which all other analyses have followed.

In Ref. [7], Corasaniti, Huterer and Melchiorri employed the SL test to constrain dark energy models such as ΛCDM model, Chap-

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lygin gas model, and interacting dark energy model. Later, Balbi and Quercellini [8] extended this analysis to more dark energy models including constant EoS model, variable EoS model, interacting dark energy model, DGP model, Cardassian model, generalized Chaplygin gas model, affine EoS model, etc. More recently, Zhang, Zhong, Zhu and He [9] further used the SL test to explore the holographic dark energy model. However, it should be pointed out that there are three holographic dark energy models: the original holographic dark energy model [10], the new agegraphic dark energy model [11], and the Ricci dark energy model [12]. Actually, in Ref. [9], only the original holographic dark energy model [10], i.e., the model in which the IR cutoff is given by the future event horizon, was investigated. Thus, along this line, as a next step, one should further explore the new agegraphic and the Ricci dark energy models with the SL test. In this Letter, this will be done. This will provide a complementary to the work of Ref. [9] and keep the investigation of holographic dark energy models more complete.

In the subsequent section, we will briefly review the new agegraphic dark energy model and the Ricci dark energy model. In Section 3, we will explore these two models with the SL test. In the last section, we will give some concluding remarks.

2. New agegraphic and Ricci dark energy models

In this section, we will briefly review the new agegraphic dark energy model and the Ricci dark energy model. In fact, these two models both belong to the holographic scenario of dark energy.

It is well known that the holographic principle is an important result of the recent research for exploring the quantum gravity [13]. This principle is enlightened by investigations of the quantum property of black holes. In a quantum gravity system, the conventional local quantum field theory will break down because it contains too many degrees of freedom that would lead to the formation of a black hole breaking the effectiveness of the quantum field theory. To reconcile this breakdown with the success of local quantum field theory in describing observed particle phenomenology, some authors proposed a relationship between the ultraviolet (UV) and the infrared (IR) cutoffs due to the limit set by the formation of a black hole [14]. The UV–IR relation in turn provides an upper bound on the zero-point energy density. In other words, if the quantum zero-point energy density $\rho_{\rm vac}$ is relevant to a UV cutoff, the total energy of the whole system with size L should not exceed the mass of a black hole of the same size, and thus we have $L^3\rho_{\rm vac} \leqslant LM_{\rm Pl}^2$. This means that the maximum entropy is of the order of $S_{\rm BH}^{3/4}$. When we take the whole universe into account, the vacuum energy related to this holographic principle is viewed as dark energy, usually dubbed holographic dark energy (its density is denoted as $\rho_{\rm de}$ hereafter).

The largest IR cutoff L is chosen by saturating the inequality so that we get the holographic dark energy density [10]

$$\rho_{\rm de} = 3c^2 M_{\rm Pl}^2 L^{-2}, \tag{1}$$

where c is a numerical constant, and $M_{\rm Pl} \equiv 1/\sqrt{8\pi G}$ is the reduced Planck mass. If we take L as the size of the current universe, for instance the Hubble radius H^{-1}, then the dark energy density will be close to the observational result. However, if one takes the Hubble scale as the IR cutoff, the holographic dark energy seems not to be capable of leading to an accelerating universe [15]. The first viable version of holographic dark energy model was proposed by Li [10]. In this model, the IR length scale is taken as the event horizon of the universe. The holographic dark energy model based on the event horizon as the IR cutoff has been widely studied [16] and found to be consistent with the observational data [17,18].

There are also other two versions of the holographic dark energy, i.e., the new agegraphic dark energy model [11,19] and the Ricci dark energy model [12,20,21]. For the new agegraphic dark energy model, the IR scale cutoff is chosen to be the conformal age of the universe; for the Ricci dark energy model, the IR cutoff is taken as the average radius of the Ricci scalar curvature. We shall briefly review these two models in the following subsections.

2.1. New agegraphic dark energy model

For a spatially flat (the assumption of flatness is motivated by the inflation scenario) Friedmann–Robertson–Walker (FRW) universe with matter component $\rho_{\rm m}$ and dark energy component $\rho_{\rm de}$, the Friedmann equation reads

$$3M_{\rm Pl}^2 H^2 = \rho_{\rm m} + \rho_{\rm de}, \tag{2}$$

or equivalently,

$$E(z) \equiv \frac{H(z)}{H_0} = \left(\frac{\Omega_{\rm m0}(1+z)^3}{1-\Omega_{\rm de}}\right)^{1/2}, \tag{3}$$

where $H \equiv \dot{a}/a$ is the Hubble parameter, $\Omega_{\rm m0}$ is the present fractional matter density, and $\Omega_{\rm de} \equiv \frac{\rho_{\rm de}}{\rho_c} = \frac{\rho_{\rm de}}{3M_{\rm Pl}^2 H^2}$ is the fractional dark energy density.

In the old version of the agegraphic dark energy model [22], the IR cutoff is chosen as the age of the universe T (here it should be pointed out that the light speed has already been taken as 1, so time and length have the same dimension). However, there are some inner inconsistencies in this model; for details see Ref. [11]. So, in this Letter, we only discuss the new version of the agegraphic dark energy model. In the new agegraphic dark energy model, the IR cutoff is chosen to be the conformal age of the universe,

$$\eta \equiv \int_0^t \frac{dt}{a} = \int_0^a \frac{da}{a^2 H}, \tag{4}$$

so the density of the new agegraphic dark energy is

$$\rho_{\rm de} = 3n^2 M_{\rm Pl}^2 \eta^{-2}. \tag{5}$$

To distinguish from the original holographic dark energy model, a new constant parameter n is used to replace the former parameter c. Taking derivative for Eq. (5) with respect to $x = \ln a$ and making use of Eq. (4), we get

$$\rho_{\rm de}' = -2\rho_{\rm de}\frac{\sqrt{\Omega_{\rm de}}}{na}. \tag{6}$$

This means that the EoS of the new agegraphic dark energy is

$$w_{\rm de} = -1 + \frac{2}{3n}\frac{\sqrt{\Omega_{\rm de}}}{a}. \tag{7}$$

Taking derivative for $\Omega_{\rm de} = n^2/(H^2\eta^2)$, and considering Eq. (4), we obtain

$$\Omega_{\rm de}' = 2\Omega_{\rm de}\left(\epsilon - \frac{\sqrt{\Omega_{\rm de}}}{na}\right), \tag{8}$$

where

$$\epsilon = \frac{3}{2}(1 + w_{\rm de}\Omega_{\rm de}) = \frac{3}{2} - \frac{3}{2}\Omega_{\rm de} + \frac{\Omega_{\rm de}^{3/2}}{na}. \tag{9}$$

Hence, we get the equation of motion for $\Omega_{\rm de}$,

$$\Omega_{\rm de}' = \Omega_{\rm de}(1-\Omega_{\rm de})\left(3 - \frac{2}{n}\frac{\sqrt{\Omega_{\rm de}}}{a}\right), \tag{10}$$