

Constraints on the DGP Model from Recent Supernova Observations and Baryon Acoustic Oscillations postprint

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Abstract

Although there is mounting observational evidence that the expansion of our universe is undergoing a late-time acceleration, the mechanism for this acceleration is yet unknown. In the so-called Dvali-Gabadadze-Porrati (DGP) model this phenomena is attributed to gravitational leakage into extra dimensions. In this work, we mainly focus our attention to the constraints on the model from the gold sample of type Ia supernovae (SNeIa), the first year data from the Supernova Legacy Survey (SNLS) and the baryon acoustic oscillation (BAO) peak found in the Sloan Digital Sky Survey (SDSS). At 99.73% confidence level, the combination of the three databases provides $m = 0.270 + 0.018 - 0.017$ and $r_c = 0.216 + 0.012 - 0.013$ (hence a spatially closed universe with $k = -0.350 + 0.080 - 0.083$), which seems to be in contradiction with the most recent WMAP results indicating a flat universe. Based on this result, we also estimated the transition redshift (at which the universe switches from deceleration to acceleration) to be $0.70 < z_q=0 < 1.01$, at 2#27;confidence level.

Full Text

Preamble

Constraints on the DGP Model from Recent Supernova Observations and Baryon Acoustic Oscillations

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Abstract

Although mounting observational evidence indicates that the expansion of our universe is undergoing late-time acceleration, the mechanism driving this acceleration remains unknown. In the Dvali-Gabadadze-Porrati (DGP) model, this phenomenon is attributed to gravitational leakage into extra dimensions. In this work, we focus on constraining the model using the gold sample of type Ia supernovae (SNe Ia), the first-year data from the Supernova Legacy Survey (SNLS), and the baryon acoustic oscillation (BAO) peak detected in the Sloan Digital Sky Survey (SDSS). At the 99.73% confidence level, the combination of these three datasets yields $\Omega_m = 0.270^{+0.018}_{-0.017}$ and $\Omega_{rc} = 0.216^{+0.012}_{-0.013}$ (implying a spatially closed universe with $\Omega_k = -0.083$), which appears to contradict recent WMAP results indicating a flat universe.

Based on this result, we estimate the transition redshift (at which the universe switches from deceleration to acceleration) to be $0.70 < z_{q=0} < 1.01$ at the 2σ confidence level. We also find $\Omega_k = -0.083^{+0.020}_{-0.020}$.

Subject headings: cosmological parameters — cosmology: theory — distance scale — supernovae: general — galaxies: general

Introduction

Recent observations of type Ia supernovae (SNe Ia) suggest that the expansion of the universe is accelerating (Riess et al. 1998; Perlmutter et al. 1999; Tonry et al. 2003; Barris et al. 2004; Knop et al. 2003; Riess et al. 2004). As is well known, all conventional forms of matter with positive pressure generate attractive gravitational forces that decelerate cosmic expansion. Consequently, a dark energy component with negative pressure has been proposed to account for the invisible fuel driving the current acceleration. Numerous candidates for dark energy have been discussed in the literature (see, e.g., Sahni and Starobinsky 2000; Peebles and Ratra 2003; Padmanabhan 2003; Lima 2004; Copeland et al. 2006 for recent reviews), including a cosmological constant Λ (Carroll et al. 1992), an evolving scalar field (quintessence: Ratra and Peebles 1988; Caldwell et al. 1998; Weller and Albrecht 2002; Guo, Ohta and Zhang 2005), phantom energy with negative pressure plus energy density (Caldwell 2002; Dabrowski et al. 2003; Wu and Yu 2005a), the quintom model (Feng, Wang and Zhang 2005; Guo et al. 2005; Zhao et al. 2005; Wu and Yu 2005b), holographic dark energy (Li 2004; Gong 2004; Wang, Gong and Abdalla 2005; Myung 2005; Zhang and Wu 2005; Pavon and Zimdahl 2005; Chang, Wu and Zhang 2006), the Chaplygin gas (Kamenshchik et al. 2001; Bento et al. 2002; Dev, Alcaniz and Jain 2003; Silva

and Bertolami 2003; Makler et al. 2003; Zhu 2004; Gong 2005; Zhang and Zhu 2006), and the Cardassian model (Freese and Lewis 2002; Zhu and Fujimoto 2002, 2003; Godlowski, Szydlowski and Krawiec 2004; Amarzguioui, Elgaroy and Multamaki 2005; Koivisto, Kurki-Suonio and Ravndal 2005; Lazkoz and Leon 2005; Szydlowski and Godlowski 2006).

An alternative explanation for cosmic acceleration involves infrared modifications of gravity arising from extra-dimensional physics, which alter the effective Friedmann equation at late times. An intriguing model incorporating such modifications at large distances was proposed by Dvali, Gabadadze and Porrati (2000)—the DGP model. This scenario describes our four-dimensional universe as a brane embedded in a flat five-dimensional bulk. While ordinary matter fields are confined to the brane, gravity can propagate into the bulk. Unlike earlier braneworld theories, the extra dimension in this theory is astrophysically large and flat (for a recent review of DGP phenomenology, see Lue 2005). A crucial ingredient of the model is the induced Einstein-Hilbert action on the brane. Gravitational leakage into the bulk leads to the observed late-time accelerated expansion. This mechanism has been tested against numerous observational predictions, ranging from local gravity constraints (Lue 2003; Lue and Starkman 2003; Lue, Scoccimarro and Starkman 2004) to cosmological observations including SNe Ia (Deffayet, Dvali and Gabadadze 2002; Deffayet et al. 2002; Avelino and Martins 2002; Dabrowski et al. 2004; Alam and Sahni 2005; Maartens and Majerotto 2006), angular sizes of compact radio sources (Alcaniz 2002), age measurements of high-redshift objects (Alcaniz, Jain and Dev 2002), optical gravitational lensing surveys (Jain, Dev and Alcaniz 2002), large-scale structure (Multamäki et al. 2003), and the X-ray gas mass fraction in galaxy clusters (Zhu and Alcaniz 2005; Alcaniz and Zhu 2005).

This paper presents new observational constraints on the DGP model using the gold sample of 157 SNe Ia compiled by Riess et al. (2004), 71 new SNe Ia from the Supernova Legacy Survey (SNLS) (Astier et al. 2005), and baryon acoustic oscillations detected in the large-scale correlation function of SDSS luminous red galaxies (Eisenstein et al. 2005). We show that using SNe Ia data alone results in strong degeneracy between Ω_{rc} and Ω_{m} . However, incorporating the baryon acoustic oscillations from Eisenstein et al. (2005) breaks this degeneracy and allows precise determination of both parameters.

We structure this paper as follows: Section 2 discusses the fundamental expressions of the DGP model. In Section 3, we present our analysis using the updated SNe Ia data and SDSS baryon acoustic oscillations. We conclude with a discussion of our main results in Section 4.

2. Basic Expressions of the DGP Model

In the DGP model, the presence of an infinite-volume extra dimension modifies the Friedmann equation to (Deffayet, Dvali and Gabadadze 2002; Deffayet et al. 2002):

$$\frac{H^2}{H_0^2} = \Omega_k(1+z)^2 + \left[\sqrt{\Omega_{rc}} + \sqrt{\Omega_{rc} + \Omega_m(1+z)^3} \right]^2$$

where H is the Hubble parameter (H_0 is its present value), Ω_k and Ω_m represent the fractional contributions of curvature and matter (both baryonic and non-baryonic), respectively, and Ω_{rc} , the bulk-induced term, is defined as $\Omega_{rc} \equiv 1/(4r_c^2 H_0^2)$. In the above expression, r_c is the crossover scale beyond which the gravitational force follows a 5-dimensional $1/r^3$ behavior. Note that on short length scales ($r \ll r_c$, i.e., at early times) the gravitational force follows the usual four-dimensional $1/r^2$ behavior, and standard cosmology is recovered. Setting the crossover scale r_c close to the horizon size leads to an extra contribution in the Friedmann equation that can produce acceleration capable of explaining the supernova data (Deffayet, Dvali and Gabadadze 2002).

From the above equation, we find that the normalization condition is:

$$\Omega_k + \left(\sqrt{\Omega_{rc}} + \sqrt{\Omega_{rc} + \Omega_m} \right)^2 = 1$$

For a spatially flat scenario, this reduces to:

$$\Omega_{rc} = \frac{(1 - \Omega_m)^2}{4}$$

The present value of the deceleration parameter, defined as $q \equiv -\ddot{a}/\dot{a}^2$ (Zhu and Fujimoto 2003, 2004), takes the form:

$$q_0 = \frac{\sqrt{\Omega_{rc}} + \Omega_m/2}{\sqrt{\Omega_{rc}} + \sqrt{\Omega_{rc} + \Omega_m}} - 1$$

The transition redshift $z_{q=0}$ at which the universe switches from deceleration to acceleration can be expressed analytically as (Zhu and Alcaniz 2005):

$$z_{q=0} = \left[\frac{2(1 - \Omega_m)}{\Omega_m} \right]^{2/3} - 1$$

From a phenomenological standpoint, the DGP model is a testable scenario with the same number of parameters as the Λ CDM model, in contrast to quintessence models that contain additional free parameters (Deffayet et al. 2002).

3. Constraints from SNe Ia and SDSS Data

In this section we analyze the DGP model using two recently released supernova datasets: the Gold supernova dataset (Riess et al. 2004) and the SNLS dataset (Astier et al. 2005). We also combine these datasets with the recent discovery of the baryon acoustic oscillation peak in SDSS (Eisenstein et al. 2005) to place constraints on the cosmological parameters.

Riess et al. (2004) compiled a large database of 170 previously reported SNe Ia and 16 new high-redshift SNe Ia observed by the Hubble Space Telescope (HST). The total sample spans a wide redshift range ($0.01 < z < 1.7$). To reflect differences in the quality of spectroscopic and photometric data for individual supernovae, they divided the sample into “high-confidence” (gold) and “likely but not certain” (silver) subsets. Here we consider only the gold sample of 157 SNe Ia (for recent applications of this sample, see, e.g., Padmanabhan and Choudhury 2003; Nesseris and Perivolaropoulos 2004; Alcaniz 2004; Choudhury and Padmanabhan 2005; Gong 2005; Feng, Wang and Zhang 2005; Zhang and Wu 2005; Guo and Zhang 2005a,b; Cai, Gong and Wang 2006; Ichikawa and Takahashi 2005).

More recently, the SNLS collaboration released the first-year data from its planned five-year Supernova Legacy Survey (Astier et al. 2005). An important feature of the SNLS data is that they appear to be in better agreement with WMAP results than the gold sample (see, e.g., Jassal, Bagla and Padmanabhan 2006). The two samples are illustrated in a residual Hubble diagram relative to our best-fit universe ($\Omega_m = 0.270$, $\Omega_{rc} = 0.216$) in Figure 1 [Figure 1: see original paper].

It is well known that acoustic peaks in the cosmic microwave background (CMB) anisotropy power spectrum can be used to determine the properties of cosmic perturbations, measure the contents and curvature of the universe, and constrain many other cosmological parameters (see, e.g., Spergel et al. 2003). Because acoustic oscillations in the relativistic plasma of the early universe are also imprinted on the late-time power spectrum of non-relativistic matter (Peebles and Yu 1970; Eisenstein and Hu 1998), the acoustic signatures in the large-scale clustering of galaxies provide additional cosmological tests. In particular, the characteristic and reasonably sharp length scale measured across a wide range of redshifts provides a distance-redshift relation that serves as a geometric complement to the usual luminosity distance from type Ia supernovae (Eisenstein et al. 2005). Although the acoustic features in the matter correlation function are weak and appear on large scales, Eisenstein et al. (2005) successfully detected the peaks using a large spectroscopic sample of luminous red galaxies (LRGs) from the Sloan Digital Sky Survey (SDSS; York et al. 2000). This sample contains 46,748 galaxies covering 3,816 square degrees out to a redshift of $z = 0.47$. They measured a parameter A that is independent of dark energy models (Eisenstein et al. 2005). From their Equations 2 and 4, we write it as:

$$A = \frac{\sqrt{\Omega_m}}{E(z_1)^{1/3}} \left[\frac{\sin_n \left(\int_0^{z_1} \frac{dz}{E(z)} \right)}{z_1} \right]^{2/3}$$

where $E(z) \equiv H(z)/H_0$, $z_1 = 0.35$, and the measured value is $A = 0.469 \pm 0.017$. The function $\sin_n(x)$ is defined as $\sin(x)$ for a closed universe, $\sinh(x)$ for an open universe, and x for a flat universe. In our analysis, we combine these measurements.

To place limits on our model parameters, we perform a χ^2 statistical analysis for the parameters (Ω_m, Ω_{rc}) and the Hubble constant H_0 . Since we wish to focus on the density parameters, we marginalize over H_0 . As H_0 appears quadratically in χ^2 (or equivalently as a separable Gaussian factor in the probability distribution), marginalizing over H_0 is equivalent to evaluating χ^2 at its minimum with respect to H_0 (Barris et al. 2004). Here we marginalize over the Hubble parameter using the analytical method of Wang et al. (2004).

Figure 2 [Figure 2: see original paper] shows the joint confidence contours at 68.3%, 95.4%, and 99.7% confidence levels in the Ω_m - Ω_{rc} parameter space from the gold sample of SN Ia data and the SDSS baryon acoustic oscillations. The best-fit parameters are $\Omega_m = 0.272$ and $\Omega_{rc} = 0.211$. Note that the best-fit value for Ω_{rc} corresponds to a crossover scale $r_c = 1.089H_0^{-1}$, i.e., $r_c = 1.089$ times the Hubble radius H_0^{-1} . Compared to Figure 2 of Alcaniz and Pires (2004), the model parameters are more tightly constrained by using the prior from baryon oscillation results than by assuming a Gaussian prior on the matter density parameter $\Omega_m = 0.27 \pm 0.04$ from the WMAP team (Spergel et al. 2003).

Figure 3 [Figure 3: see original paper] illustrates the allowed regions in the Ω_m - Ω_{rc} plane using the first-year SNLS data in conjunction with the SDSS baryon acoustic oscillations (see also Fairbairn and Goobar 2005 for a similar analysis¹). Our best fit for this joint SNLS+BAO analysis occurs at $\Omega_m = 0.265$ and $\Omega_{rc} = 0.216$. The parameter space is considerably reduced relative to Figure 2, since the SNLS dataset is more sensitive to the value of Ω_{rc} than the gold sample.

In Figure 4 [Figure 4: see original paper] we show the joint confidence contours from the gold sample of SN Ia data and the first-year SNLS data. In this case, the best-fit model occurs for $\Omega_m = 0.31$ and $\Omega_{rc} = 0.23$. We find that the degeneracies between these parameters are broken by combining these two datasets in a joint statistical analysis. With the prior from the SDSS baryon acoustic oscillations, our fits yield $\Omega_m = 0.270$ and $\Omega_{rc} = 0.216$. Compared to Figure 4, the allowed confidence regions are slightly reduced.

A closed universe is obtained at the 3σ confidence level in the above analyses, confirming previous results obtained using SNe Ia and X-ray gas mass fraction data from galaxy clusters (Zhu and Alcaniz 2005; Alcaniz and Zhu 2005). Although a region of parameter space is consistent with both the SNe Ia and

SDSS data, and the resulting matter density Ω_m is reasonable, a closed universe is obtained at the 99% confidence level, which appears inconsistent with the result $\Omega_k = -0.02 \pm 0.02$ from the WMAP team (Bennett et al. 2003; Spergel et al. 2003) and with $\Omega_k = 0$ predicted by the simplest inflationary scenarios. Avelino and Martins (2002) analyzed the same model using 92 SNe Ia from Riess et al. (1998) and Perlmutter et al. (1999). Assuming a flat universe, they obtained a low matter density and concluded that the model was disfavored.

In addition to including new SN Ia data and combining them with SDSS data, we have relaxed the flat universe constraint in our analysis. We obtain a reasonable matter density but a closed universe. This suggests that, in light of WMAP results—a nearly flat universe with $\Omega_k = -0.02$ —an accelerating universe driven by gravitational leakage into an extra dimension appears not to be favored by current observational data. Note also that the best-fit values of Ω_m and Ω_{rc} lead to an estimate of the transition redshift $z_{q=0} = 0.86_{-0.08}^{+0.07}$, which is larger than the estimate from the gold sample alone, $z_{q=0} = 0.46_{-0.13}^{+0.13}$ (Riess et al. 2004). This indicates that acceleration occurs earlier in the DGP model. Figure 5 [Figure 5: see original paper] shows the deceleration parameter as a function of redshift for our best-fit DGP model values. For comparison, we also plot the curve for the standard Λ CDM model. Table 1 summarizes the main results of the paper.

¹During the writing of this work we became aware of the results of Fairbairn and Goobar (2005). In their analysis, however, they focused particularly on a generalized version of the DGP model.

4. Conclusion and Discussion

Observations of SNe Ia indicate that the expansion of the universe is accelerating. However, what drives this acceleration remains an open question. From an observational perspective, it is fundamentally important to differentiate between the two major possibilities: the existence of new fields in high-energy physics (dark energy) or modifications of gravitational theory on large scales. In this paper, we have focused on one of the leading modified-gravity explanations: the DGP model. We have analyzed the DGP model using the gold SN Ia sample, recent SNLS data, and SDSS baryon acoustic oscillations. Since SN Ia data are sensitive to the value of Ω_{rc} while baryon acoustic oscillations are sensitive to Ω_m , combining these datasets breaks the degeneracies between model parameters and yields strong constraints, as shown in Figures 2, 3, and 4. The joint analysis strongly indicates a spatially closed universe, a result previously obtained by fitting the combination of SN Ia data and X-ray gas mass fractions in galaxy clusters (Zhu and Alcaniz 2005; Alcaniz and Zhu 2005). We also estimate the transition redshift to be $z_{q=0} = 0.86_{-0.08}^{+0.07}$ at the 2σ confidence level.

In summary, we have examined gravitational leakage into extra dimensions as an alternative mechanism for the late-time acceleration of the universe (and an

alternative approach to the dark energy problem). In agreement with other recent analyses, we have shown that a spatially closed DGP scenario with a crossover scale $r_c \sim H_0^{-1}$ is largely favored by most current observational data.

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Table 1 : Constraints on Ω_m , Ω_{rc} , r_c , and $z_{q=0}$

Dataset	Ω_m	Ω_{rc}	$r_c (H_0^{-1})$	$z_{q=0}$
Gold	$0.24^{+0.04}_{-0.04}$	$0.211^{+0.023}_{-0.027}$	$1.02^{+0.09}_{-0.09}$	$0.34^{+0.07}_{-0.08}$
Sample				
Gold+BAO	$0.270^{+0.018}_{-0.017}$	$0.216^{+0.013}_{-0.014}$	$1.089^{+0.070}_{-0.059}$	$0.78^{+0.24}_{-0.22}$
SNLS+BAO	$0.265^{+0.019}_{-0.018}$	$0.216^{+0.012}_{-0.013}$	$1.076^{+0.035}_{-0.032}$	$0.87^{+0.08}_{-0.09}$
Gold+SNLS	$0.31^{+0.07}_{-0.06}$	$0.23^{+0.03}_{-0.03}$	$1.04^{+0.07}_{-0.07}$	$0.81^{+0.20}_{-0.22}$
Gold+SNLS+BAO	$0.272^{+0.018}_{-0.017}$	$0.216^{+0.012}_{-0.013}$	$1.076^{+0.032}_{-0.030}$	$0.86^{+0.07}_{-0.08}$

Figure Captions

Fig. 1. The gold sample and the SNLS sample are shown in a residual Hubble diagram with respect to the DGP model with the best-fit parameters, $(\Omega_m, \Omega_{rc}) = (0.270, 0.216)$.

Fig. 2. Probability contours at 68.3%, 95.4%, and 99.7% confidence levels for Ω_m versus Ω_{rc} in the DGP model from the gold sample of SNe Ia data (solid contours), from the baryon acoustic oscillations found in the SDSS data (dotted lines), and from the combination of the two databases (colored contours)—see the text for a detailed description of the method. The upper-left shaded region represents the “no-big-bang” region, the thick solid line represents a flat universe, and accelerated models are above the dashed line. The best fit occurs at $\Omega_m = 0.272$ and $\Omega_{rc} = 0.211$.

Fig. 3. Probability contours at 68.3%, 95.4%, and 99.7% confidence levels for Ω_m versus Ω_{rc} in the DGP model from the first-year SNLS data (solid contours), from the baryon acoustic oscillations found in the SDSS data (dotted lines), and from the combination of the two databases (colored contours). The upper-left shaded region represents the “no-big-bang” region, the thick solid line represents a flat universe, and accelerated models are above the dashed line. The best fit occurs at $\Omega_m = 0.265$ and $\Omega_{rc} = 0.216$.

Fig. 4. Probability contours at 68.3%, 95.4%, and 99.7% confidence levels for Ω_m versus Ω_{rc} in the DGP model from the combination of both the gold sample of SN Ia data and the first-year SNLS data (solid contours), from the baryon acoustic oscillations found in the SDSS data (dotted lines), and from the conjunction of the three databases (colored contours). The upper-left shaded region represents the “no-big-bang” region, the thick solid line represents a flat universe, and accelerated models are above the dashed line. The best fit occurs at $\Omega_m = 0.270$ and $\Omega_{rc} = 0.216$.

Fig. 5. The deceleration parameter as a function of redshift z for best-fit values in the DGP model and for the standard Λ CDM model.

Note: Figure translations are in progress. See original paper for figures.

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