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ACCELERATING UNIVERSE FROM GRAVITATIONAL LEAKAGE INTO EXTRA DIMENSIONS: TESTING WITH TYPE Ia SUPERNOVAE

ZONG-HONG ZHU
Department of Astronomy, Beijing Normal University, Beijing 100875, China; zhuzh@bnu.edu.cn

AND

JAILSON S. ALCANIZ
Departamento de Astronomia, Observatório Nacional, 20921-400 Rio de Janeiro, RJ, Brazil; alcaniz@on.br
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ABSTRACT

There is mounting observational evidence that the expansion of our universe is undergoing an acceleration. A dark energy component has usually been invoked as the most feasible mechanism for the acceleration. However, it is desirable to explore alternative possibilities motivated by particle physics before adopting such an untested entity. In this work, we focus our attention on an acceleration mechanism arising from gravitational leakage into extra dimensions. We test this scenario with high-z Type Ia supernovae compiled by Tonry and coworkers and recent measurements of the X-ray gas mass fractions in clusters of galaxies published by Allen and coworkers. A combination of the two databases gives, at a 99% confidence level, $\Omega_m = 0.29^{+0.04}_{-0.02}$, $\Omega_{r_c} = 0.21 \pm 0.08$, and $\Omega_k = -0.36^{+0.31}_{-0.35}$, indicating a closed universe. We then constrain the model using the test of the turnaround redshift, $z_{q=0}$, at which the universe switches from deceleration to acceleration. We show that, in order to explain that acceleration happened earlier than $z_{q=0} = 0.6$ within the framework of gravitational leakage into extra dimensions, a low matter density, $\Omega_m < 0.27$, or a closed universe is necessary.

Subject headings: cosmological parameters — cosmology: theory — distance scale — supernovae: general — X-rays: galaxies: clusters

Online material: color figures

1. INTRODUCTION

The recent well-known distance measurements of distant Type Ia supernovae (SNe Ia) suggest an accelerating universe at large scales (Riess et al. 1998, 2004; Perlmutter et al. 1999; Tonry et al. 2003; Barris et al. 2004; Knop et al. 2003). The cosmic acceleration has also been confirmed, independently of the SN Ia magnitude-redshift relation, by the observations of the cosmic microwave background anisotropies (*Wilkinson Microwave Anisotropy Probe* [*WMAP*]; Bennett et al. 2003) and the large-scale structure in the distribution of galaxies (Sloan Digital Sky Survey; Tegmark et al. 2004a, 2004b). It is well known that all known types of matter with positive pressure generate attractive forces and decelerate the expansion of the universe. Given this, a dark energy component with negative pressure was generally suggested as the invisible fuel that drives the current acceleration of the universe. There are a huge number of candidates in the literature for the dark energy component, such as a cosmological constant Λ (Carroll et al. 1992; Krauss & Turner 1995; Ostriker & Steinhardt 1995; Chiba & Yoshii 1999); a decaying vacuum energy density or a time-varying Λ-term (Ozer & Taha 1987; Vishwakarma 2001); an evolving scalar field (referred to by some as quintessence; Ratra & Peebles 1988; Caldwell et al. 1998; Wang & Lovelace 2001; Weller & Albrech 2002; Gong 2002, 2004; Li et al. 2002a, 2002b; Chen & Ratra 2003; Mukherjee et al. 2003); the phantom energy, in which the sum of the pressure and energy density is negative (Caldwell 2002; Dabrowski et al. 2003; Wang et al. 2004); the so-called X-matter (Turner & White 1997; Zhu 1998; Podariu & Ratra 2001; Zhu et al. 2001; Alcaniz et al. 2003b; Lima et al. 2003; Feng et al. 2004; Dai et al. 2004); the Chaplygin gas (Kamenshchik et al. 2001; Bento et al. 2002; Alam et al. 2003; Alcaniz et al. 2003a; Dev et al. 2003; Silva & Bertolami 2003; Makler et al. 2003); and the Cardassian model (Freese & Lewis 2002; Zhu & Fujimoto 2002, 2003; Sen & Sen 2003; Wang et al. 2003; Frith 2004; Gong & Duan 2004a, 2004b).

However, dark energy currently has no convincing direct laboratory evidence for its existence, so it is desirable to explore alternative possibilities motivated by particle physics before adopting such a component. In this respect the models that make use of the ideas of branes and extra dimensions to obtain an accelerating universe are particularly interesting (Randall & Sundrum 1999a, 1999b). Within the framework of these braneworld cosmologies, our observable universe is assumed to be a surface or brane embedded in a higher dimensional bulk spacetime in which gravity could spread. The bulk gravity sees its own curvature term on the brane, which accelerates the universe without dark energy (Randall 2002). Recently, on the basis of the model of brane-induced gravity from Dvali et al. (2000), Deffayet and coworkers (Deffayet 2001; Deffayet et al. 2002a) proposed a scenario in which the observed late time acceleration of the expansion of the universe is caused by gravitational leakage into an extra dimension, and the Friedmann equation is modified as follows:

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

where H is the Hubble parameter as a function of redshift z (H_0 is its value at the present) and Ω_k, Ω_{r_c}, and Ω_m represent the fractional contribution of curvature, the bulk-induced term, and the matter (both baryonic and nonbaryonic), respectively. The value of Ω_{r_c} is defined as $\Omega_{r_c} \equiv 1/4r_c^2H_0^2$, where r_c is the crossover scale beyond which the gravitational force follows the five-dimensional $1/r^3$ behavior. From a phenomenological standpoint, it is a testable scenario with the same number of parameters as a cosmological constant model, contrasting with models of quintessence that have an additional free function, the equation of state, to be determined (Deffayet et al. 2002b). Such a possible mechanism for cosmic acceleration has triggered investigations aiming to constrain this scenario using various cosmological observations, such as SNe Ia (Avelino & Martins 2002; Deffayet et al. 2002a, 2002b; Godlowski & Szydlowski 2004), angular size of compact radio sources (Alcaniz 2002), the age measurements of high-z objects (Alcaniz et al. 2002), the optical gravitational lensing surveys (Jain et al. 2002), and the large-scale structures (Multamäki et al. 2003). But the results are disperse and somewhat controversial, with most of them claiming good agreement between the data and the model and some of them ruling out gravitational leakage into an extra dimension as a feasible mechanism for cosmic acceleration.

The purpose of this work is to quantitatively confront the scenario with the updated SN Ia sample compiled by Tonry et al. (2003) and to try to constrain the model parameters more accurately. We show that, although the two parameters, Ω_{r_c} and Ω_m, are degenerate and there is a range on the parameter plane that is consistent with the SN Ia data, a closed universe is preferred by this scenario. As is well known, the measurement of the X-ray gas mass fraction in galaxy clusters is an efficient way to determine the matter density, Ω_m, and hence can be used for breaking the degeneracy between Ω_{r_c} and Ω_m. When we combine the X-ray database published by Allen et al. (2002, 2003) with the Tonry et al. sample for analysis, we obtain a closed universe at a 99% confidence level; i.e., for the scenario of gravitational leakage into an extra dimension, a universe with curvature is favored by the combination of the two databases. We also analyze the turnaround redshift, $z_{q=0}$, at which the universe switches from deceleration to acceleration within the framework of the scenario. We show that, if the turnaround redshift happened earlier than $z_{q=0} = 0.6$, only a low matter density, $\Omega_m < 0.27$, or a closed universe can explain this transition epoch. If, however, we consider the recent estimate by Riess et al. (2004), i.e., $z_{q=0} = 0.46 \pm 0.13$, then a spatially flat scenario with $\Omega_m = 0.3$ (as suggested by clustering estimates) predicts $z_{q=0} = 0.48$, which is surprisingly close to the central value given by Riess et al. (2004). The paper is organized as follows. In the next section, we consider the observational constraints on the parameter space of the scenario arising from the updated SN Ia sample compiled by Tonry et al. (2003), as well as the combination with the X-ray gas mass fractions in galaxy clusters published by Allen et al. (2002, 2003). In § 3 we discuss the bounds on the model from the turnaround redshift, $z_{q=0}$. Finally, we present our conclusion and discussion in § 4.

2. CONSTRAINTS FROM SN Ia AND GALAXY CLUSTER DATA

Recently, Tonry et al. (2003) compiled a large database of SNe Ia from the literature and eight new SNe Ia from the High-z Supernova Search Team. Since the techniques for data analysis vary between individual SN Ia samples, the authors attempted to recompute the extinction estimates and the distance determination through the multicolor light-curve shape fitting (Riess et al. 1998), the Δm_{15} method of Phillips et al. (1999), the modified dm15 fitting (Germany 2001), and the Bayesian Adapted Template Match method (Tonry et al. 2003). Zero-point differences between each method were computed by comparing common SN measurements, distances were placed on a Hubble flow zero point (dH_0), and the median was selected as the best distance estimate (for more details of this procedure, see Tonry et al. 2003; Barris et al. 2004). Tonry et al. (2003) present redshifts and distances for 230 SNe Ia, including many objects unsuitable for cosmological analysis, such as the SNe Ia being heavily extinguished or nearby enough for velocity uncertainties to be a major problem. To determine cosmological parameters, the authors used a redshift cut of $z > 0.01$ and an extinction cut of $A_V < 0.5$ mag. The resulting sample of 172 SNe Ia is illustrated on a residual Hubble diagram with respect to an empty universe ($\Omega_m = 0, \Omega_{r_c} = 0$) in Figure 1. We use this sample to give an observational constraint on the model parameters, Ω_{r_c} and Ω_m.

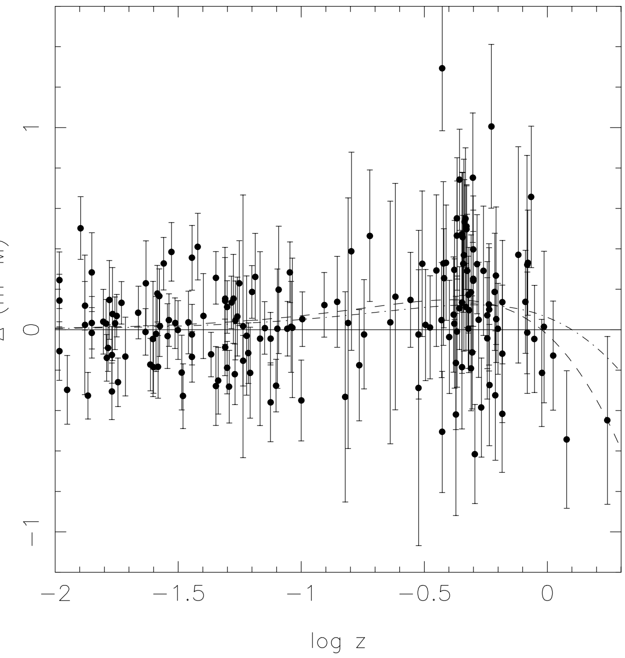

FIG. 1.—Sample of 172 SN Ia data points obtained by imposing constraints $A_V < 0.5$ and $z > 0.01$ on the 230 SN Ia sample of Tonry et al. (2003), shown in a residual Hubble diagram with respect to an empty universe. The dashed and dot-dashed lines show $(\Omega_m,\ \Omega_{r_c}) = (0.43,\ 0.26)$, our best fit, and $(\Omega_m,\ \Omega_\Lambda) = (0.3,\ 0.7)$, the standard ΛCDM model, respectively.

For the *Ansatz* equation (1), we are required to calculate χ^2 as a function of the model parameters (Ω_m, Ω_{r_c}) and the Hubble constant H_0. Following Tonry et al. (2003), we added 500 km s^{-1} divided by the redshift in quadrature to the distance error given in their Table 15 for calculating χ^2. In order to concentrate solely on the density parameters, we need to marginalize over the Hubble constant H_0. Since H_0 appears as a quadratic term in χ^2, it appears in the probability as a separable Gaussian factor to be marginalized over. Thus, marginalizing over H_0 is equivalent to evaluating χ^2 at its minimum with respect to H_0 (Barris et al. 2004). This procedure allows us to determine contours of constant probability density for the model parameters (Ω_m, Ω_{r_c}) corresponding to 68%, 95%, and 99% confidence levels, which are shown in Figure 2. The best fit happens at $\Omega_m = 0.43$ and $\Omega_{r_c} = 0.26$. As shown in Figure 2, although there is a range on the parameter plane that is consistent with the SN Ia data, a closed universe is favored. Furthermore, the two density parameters, Ω_{r_c} and Ω_m, are highly degenerate, which is

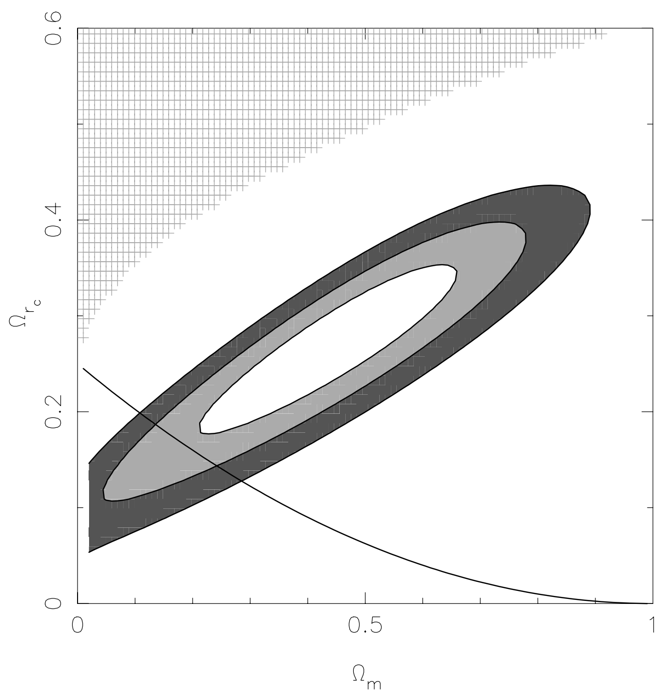

FIG. 2.—Probability contours for Ω_{r_c} and Ω_m in the model of gravitational leakage into an extra dimension for the 172 SNe Ia taken from Tonry et al. (2003); see the text for a detailed description of the method. The 68%, 95%, and 99% confidence levels in the Ω_{r_c}-Ω_m plane are shown in red, green, and yellow shaded areas, respectively. The cross-hatched region at the upper left represents the "no-big-bang" region, while the thick solid line represents the flat universe. The best fit happens at $\Omega_m = 0.43$ and $\Omega_{r_c} = 0.26$. [*See the electronic edition of the Journal for a color version of this figure.*]

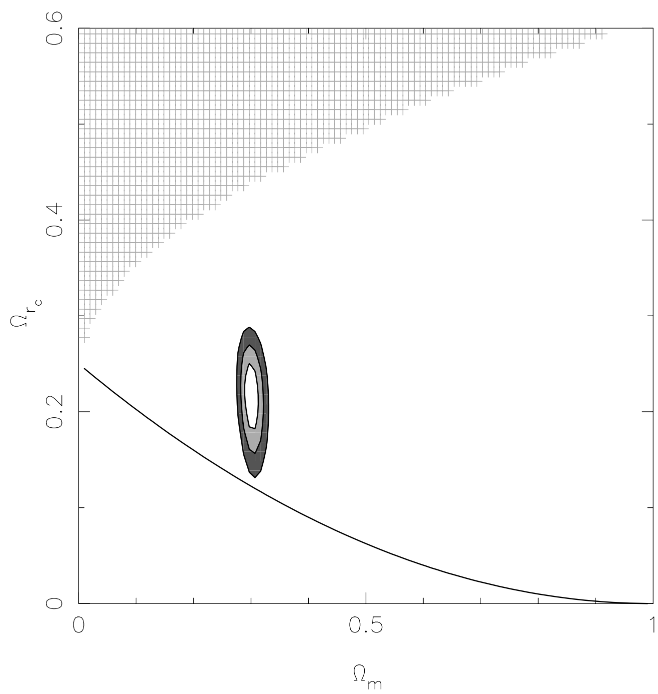

FIG. 3.—Probability contours over Ω_{r_c} and Ω_m for the combination of the 172 SNe Ia taken from Tonry et al. (2003) and the nine X-ray clusters from Allen et al. (2002, 2003). The 68%, 95%, and 99% confidence levels in the Ω_{r_c}-Ω_m plane are shown in red, green, and yellow shaded areas, respectively. The cross-hatched region at the upper left represents the "no-big-bang" region, while the thick solid line represents the flat universe. The best fit happens at $\Omega_m = 0.29$ and $\Omega_{r_c} = 0.21$, thus giving a closed universe with $\Omega_k = -0.36$. However, the results depend on the X-ray gas mass fraction data from Allen et al. (2002, 2003), in which the error bars might be on the optimistic side. [*See the electronic edition of the Journal for a color version of this figure.*]

very similar to the degeneracy between Ω_Λ and Ω_m found by Tonry et al. (2003). In order to determine Ω_{r_c} and Ω_m, an independent measurement of Ω_{r_c} or Ω_m is needed. As shown below, the X-ray gas mass fraction data of galaxy clusters are appropriate for this purpose, because the data are only sensitive to Ω_m (Allen et al. 2002, 2003).

Since clusters of galaxies are the largest virialized systems in the universe, their matter content should provide a fair sample of the matter content of the universe as a whole, and a comparison of their gas mass fractions, $f_{\rm gas} = M_{\rm gas}/M_{\rm tot}$, as inferred from X-ray observations, with the cosmic baryon fraction can provide a direct constraint on the density parameter of the universe Ω_m (White et al. 1993). Moreover, assuming the gas mass fraction is constant in cosmic time, Sasaki (1996) shows that the $f_{\rm gas}$ measurements of clusters of galaxies at different redshifts also provide a way to constrain other cosmological parameters describing the geometry of the universe. Recently, Allen et al. (2002, 2003) published the $f_{\rm gas}$ profiles for the 10 relaxed clusters observed by the *Chandra* satellite. Except for A963, the $f_{\rm gas}$ profiles of the other nine clusters appear to have converged or be close to converging with r_{2500}, the radius within which the mean mass density is 2500 times the critical density of the universe at the redshift of the cluster. The gas mass fraction values of these nine clusters were shown in Figure 5 of Allen et al. (2003). This database can be used to break the degeneracy between Ω_{r_c} and Ω_m mentioned above, since it has been shown that the X-ray gas mass fraction is mostly sensitive to Ω_m no matter what the cosmological model is (Allen et al. 2002; Lima et al. 2003). The probability density over the model parameters, Ω_{r_c} and Ω_m, for the nine galaxy clusters is calculated using the method described in Allen et al. (2002). Following Allen et al. (2003), we include Gaussian priors on the bias factor, $b = 0.93 \pm 0.05$, a value appropriate for hot ($kT > 5$ keV) clusters from the simulations of Bialek et al. (2001); on the Hubble constant, $h = 0.72 \pm 0.08$, the final result from the Hubble Key Project by Freedman et al. (2001); and on $\Omega_m h^2 = 0.0205 \pm 0.0018$ (O'Meara et al. 2001), from cosmic nucleosynthesis calculations constrained by the observed abundances of light elements at high redshifts. We then multiply the probability densities from the 172 SNe Ia and the nine galaxy clusters and obtain our final results on Ω_{r_c} and Ω_m, which are shown in Figure 3.

Figure 3 illustrates the 68%, 95%, and 99% confidence levels in the (Ω_m, Ω_{r_c}) plane with the red, green, and yellow shaded areas, respectively. Our fits give, at a 99% confidence level, $\Omega_m = 0.29^{+0.04}_{-0.02}$, $\Omega_{r_c} = 0.21 \pm 0.08$, and $\Omega_k = -0.36^{+0.31}_{-0.35}$. Although there is a range on the parameter plane that is consistent with both the SN Ia and the galaxy cluster data, and the resulting matter density Ω_m is reasonable, a closed universe is obtained at a 99% confidence level, which is inconsistent with the result, $\Omega_k = -0.02 \pm 0.02$, found by the *WMAP* (Bennett et al. 2003). Avelino & Martins (2002) analyzed the same model with the 92 SNe Ia from Riess et al. (1998) and Perlmutter et al. (1999). Assuming a flat universe, the authors obtained a very low matter density and claimed the model was disfavorable. In addition to including new SN Ia data from Tonry et al. (2003) and combining the X-ray data of the nine galaxy clusters, we relax the flat universe constraint of their analysis. We obtain a reasonable matter density but a closed universe. In some sense, i.e., if we assume that our universe is spatially flat, as indicated by

WMAP results, the accelerating scenario from gravitational leakage into extra dimensions does not seem to be favored by observational data. However, two points should be emphasized here. First, the same conclusion is reached by performing a similar analysis with our current standard model, i.e., a ΛCDM universe. Second, we have made heavy use of the X-ray gas mass fraction in clusters to determine the matter density. This kind of analysis depends on the assumption that $f_{\rm gas}$ values should be invariant with redshift, which has been criticized by some works in the field. For example, a recent comparison of distant clusters observed by the *XMM-Newton* and *Chandra* satellites with available local cluster samples indicates a possible evolution of the *M-T* relation with redshift; i.e., the standard paradigm on cluster gas physics needs to be revised (Vauclair et al. 2003). We should keep this point in mind when we conclude that the gravitational leakage scenario is disfavored by the databases.

3. CONSTRAINTS FROM THE TURNAROUND REDSHIFT FROM DECELERATION TO ACCELERATION

Since the scenario of gravitational leakage into extra dimensions is proposed as a possible mechanism for the cosmic acceleration, the turnaround redshift from deceleration to acceleration is expected to provide an efficient way of verifying the model. It can be shown that the deceleration parameter as a function of redshift, as well as the model parameters, takes the form (Zhu & Fujimoto 2004)

$$q(z) \equiv -\frac{\ddot{R}R}{\dot{R}^2} = -1 + \frac{1}{2}\frac{d\ln E^2}{d\ln(1+z)}, \qquad (2)$$

where $E^2(z;\ \Omega_{r_c},\ \Omega_m) = H^2(z;\ \Omega_{r_c},\ \Omega_m)/H_0$. From equation (1), we can derive the turnaround redshift at which the universe switches from deceleration to acceleration, in other words, the redshift at which the deceleration parameter vanishes, which is as follows:

$$(1+z)_{q=0} = 2\left(\frac{\Omega_{r_c}}{\Omega_m}\right)^{1/3}. \qquad (3)$$

We have shown that equation (3) is generally valid no matter what the curvature of the universe is, although it was first obtained by Avelino & Martins (2002) for a flat universe. According to Turner & Riess (2002), the value for the turnaround redshift lies in the 1 σ interval $0.6 < z_{q=0} < 1.7$. In Figure 4, the two dashed lines represent $z_{q=0} = 0.6$ and 1.7, respectively, while the hatched region at the lower right corresponds to $z_{q=0} \leq 0$, which means a decelerating universe. The thick solid line represents the flat universe. The vertical strip with cross-hatching represents the matter density $\Omega_m = 0.330 \pm 0.035$ found by Turner (2002), and the vertical dot-dashed lines show $\Omega_m = 0.2$ and 0.4, a wider range. As shown, in order to explain that cosmic acceleration started earlier than $z_{q=0} = 0.6$, either a low matter density, $\Omega_m < 0.27$, is needed on the assumption of a flat universe, or a closed universe is necessary for a higher matter density. If, however, we consider the recent estimate by Riess et al. (2004), i.e., $z_{q=0} = 0.46 \pm 0.13$, then a spatially flat scenario with $\Omega_m = 0.3$ (as suggested by clustering estimates) predicts $z_{q=0} = 0.48$, which is surprisingly close to the central value given by Riess et al. (2004).

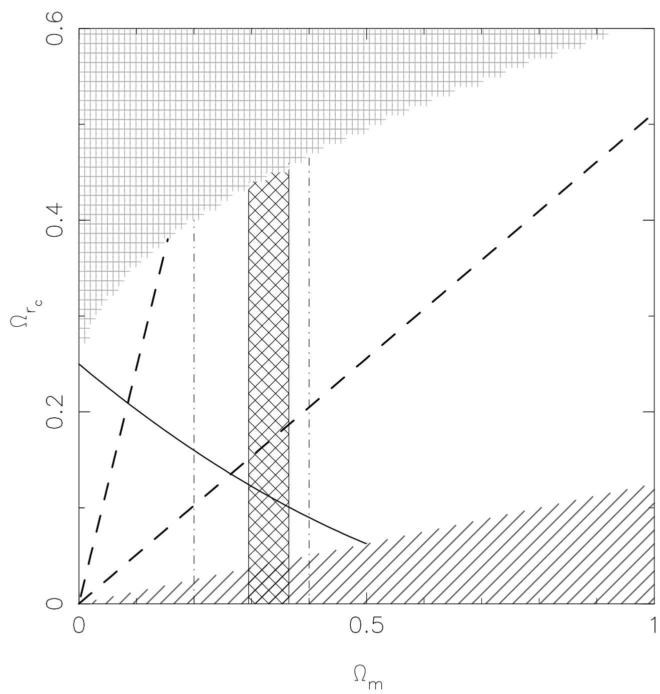

FIG. 4.—Constraints on the parameter space (Ω_{r_c}, Ω_m) of the model of gravitational leakage into an extra dimension from the turnaround redshift of acceleration. The hatched region at the lower right represents the decelerating model, and the cross-hatched region at the upper left represents the "no-big-bang" region. The right and left dashed lines indicate $z_{q=0} = 0.6$ and 1.7, respectively, while the thick solid line represents the flat universe. Thus, in order to explain that acceleration happened earlier than $z_{q=0} = 0.6$, the gravitational leakage model needs a low matter density, $\Omega_m < 0.27$, if the universe is flat. The vertical strip with cross-hatching corresponds to the matter density $\Omega_m = 0.330 \pm 0.035$ found by Turner (2002), which clearly asks for a closed universe to explain $z_{q=0} > 0.6$. For convenience, we also draw two dot-dashed lines for $\Omega_m = 0.2$ and 0.4, for which there are some ranges compatible with a flat universe. We note that a matter density of $\Omega_m < 0.27$ is also permitted by the *WMAP* data (Bennett et al. 2003). [*See the electronic edition of the Journal for a color version of this figure.*]

4. CONCLUSION AND DISCUSSION

The mounting observational evidence for an accelerating universe has stimulated renewed interest in alternative cosmologies. Generally, a dark energy component with negative pressure is invoked to explain the SN Ia results and to reconcile the inflationary flatness prediction ($\Omega_T = 1$) with the dynamical estimates of the quantity of matter in the universe ($\Omega_m \sim 0.3$). In this paper we have focused our attention on another possible acceleration mechanism, one arising from gravitational leakage into extra dimensions. In order to be consistent with the current SN Ia and X-ray cluster data, one would need a closed universe.

Recently, Lue et al. (2004) derived dynamical equations for spherical perturbations at subhorizon scales and computed the growth of large-scale structure in the framework of this scenario. A suppression of the growth of density and velocity perturbations was found for the model being considered, comparing the ΛCDM model with the same Ω_m. For the ΛCDM model with $\Omega_m = 0.3$, a perturbation of $\delta_i = 3\times10^{-3}$ at $z_i = 1000$ will collapse at $z \approx 0.66$ when its linearly extrapolated density contrast is $\delta_c = 1.689$, but for the model being considered, the collapse can only happen at $z \approx 0.35$ when its $\delta_c = 1.656$. Furthermore, the authors showed that this scenario for cosmic acceleration gave rise to a present-day fluctuation power spectrum normalization $\sigma_8 \leq 0.8$ at a 2 σ level, lower than the observed value (Lue et al. 2004).

As shown in Figure 2 of Deffayet et al. (2002a), on the assumption of a flat universe, the luminosity distance for ΛCDM increases with redshift faster than that for the model being considered (for the same Ω_m). Therefore, it is natural that, if the ΛCDM model with ($\Omega_m = 0.3, \Omega_\Lambda = 0.7, \Omega_k = 0$) is consistent with the SN Ia data, the gravitational leakage model with ($\Omega_m = 0.3, \Omega_{r_c} = 0.1225, \Omega_k = 0$) will not be, as the data are becoming enough to determine the cosmological parameters more precisely. While Deffayet et al. (2002b) showed that the gravitational leakage scenario was consistent with the 54 SNe Ia of sample C from Perlmutter et al. (1999)—see also Alcaniz & Pires (2004)—Avelino & Martins (2002) claimed that this proposal was disfavored by the dataset of 92 SNe Ia from Riess et al. (1998) and Perlmutter et al. (1999) (combined via the procedure described in Wang 2000 and Wang & Garnavich 2001). We, however, think that only with a more general analysis, a joint investigation involving different classes of cosmological tests, will it be possible to delimit the Ω_m-Ω_{r_c} plane more precisely and to test more properly the consistency of these scenarios. Such an analysis will appear in a forthcoming paper (Alcaniz & Zhu 2005).

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REFERENCES

Alam, U., Sahni, V., Saini, T. D., & Starobinsky, A. A. 2003, MNRAS, 344, 1057
Alcaniz, J. S. 2002, Phys. Rev. D, 65, 123514
Alcaniz, J. S., Jain, D., & Dev, A. 2002, Phys. Rev. D, 66, 067301
———. 2003a, Phys. Rev. D, 67, 043514
Alcaniz, J. S., Lima, J. A. S., & Cunha, J. V. 2003b, MNRAS, 340, L39
Alcaniz, J. S., & Pires, N. 2004, Phys. Rev. D, 70, 047303
Alcaniz, J. S., & Zhu, Z.-H. 2005, preprint (astro-ph/0411604)
Allen, S. W., Schmidt, R. W., & Fabian, A. C. 2002, MNRAS, 334, L11
Allen, S. W., Schmidt, R. W., Fabian, A. C., & Ebeling, H. 2003, MNRAS, 342, 287
Avelino, P. P., & Martins, C. J. A. P. 2002, ApJ, 565, 661
Barris, B. J., et al. 2004, ApJ, 602, 571
Bennett, C. L., et al. 2003, ApJS, 148, 1
Bento, M. C., Bertolami, O., & Sen, A. A. 2002, Phys. Rev. D, 66, 043507
Bialek, J. J., Evrard, A. E., & Mohr, J. J. 2001, ApJ, 555, 597
Caldwell, R. 2002, Phys. Lett. B, 545, 23
Caldwell, R., Dave, R., & Steinhardt, P. J. 1998, Phys. Rev. Lett., 80, 1582
Carroll, S., Press, W. H., & Turner, E. L. 1992, ARA&A, 30, 499
Chen, G., & Ratra, B. 2003, ApJ, 582, 586
Chiba, M., & Yoshii, Y. 1999, ApJ, 510, 42
Dabrowski, M. P., Stachowiak, T., & Szydlowski, M. 2003, Phys. Rev. D, 68, 103519
Dai, Z., Liang, E. W., & Xu, D. 2004, ApJ, 612, L101
Deffayet, C. 2001, Phys. Lett. B, 502, 199
Deffayet, C., Dvali, G., & Gabadadze, G. 2002a, Phys. Rev. D, 65, 044023
Deffayet, C., Landau, S. J., Raux, J., Zaldarriaga, M., & Astier, P. 2002b, Phys. Rev. D, 66, 024019
Dev, A., Alcaniz, J. S., & Jain, D. 2003, Phys. Rev. D, 67, 023515
Dvali, G., Gabadadze, G., & Porrati, M. 2000, Phys. Lett. B, 485, 208
Feng, B., Wang, X., & Zhang, X. 2004, preprint (astro-ph/0404224)
Freedman, W., et al. 2001, ApJ, 553, 47
Freese, K., & Lewis, M. 2002, Phys. Lett. B, 540, 1
Frith, W. J. 2004, MNRAS, 348, 916
Germany, L. M. 2001, Ph.D. thesis, Australian National Univ.
Godlowski, W., & Szydlowski, M. 2004, Gen. Relativ. Gravitation, 36, 767
Gong, Y. 2002, Classical Quantum Gravity, 19, 4537
———. 2004, Int. J. Mod. Phys. D, in press (astro-ph/0401207)
Gong, Y., & Duan, C.-K. 2004a, Classical Quantum Gravity, 21, 3655
———. 2004b, MNRAS, 352, 847
Jain, D., Dev, A., & Alcaniz, J. S. 2002, Phys. Rev. D, 66, 083511
Kamenshchik, A., Moschella, U., & Pasquier, V. 2001, Phys. Lett. B, 511, 265
Knop, R. A., et al. 2003, ApJ, 598, 102
Krauss, L. M., & Turner, M. S. 1995, Gen. Relativ. Gravitation, 27, 1137
Li, M., Lin, W., Zhang, X., & Brandenberger, R. 2002a, Phys. Rev. D, 65, 023519
Li, M., Wang, X., Feng, B., & Zhang, X. 2002b, Phys. Rev. D, 65, 103511
Lima, J. A. S., Cunha, J. V., & Alcaniz, J. S. 2003, Phys. Rev. D, 68, 023510
Lue, A., Scoccimarro, R., & Starkman, G. D. 2004, Phys. Rev. D, 69, 124015
Makler, M., Quinet de Oliveira, S., & Waga, I. 2003, Phys. Rev. D, 68, 123521
Mukherjee, P., Banday, A. J., Riazuelo, A., Gorski, K. M., & Ratra, B. 2003, ApJ, 598, 767
Multamäki, T., Gaztanaga, E., & Manera, M. 2003, MNRAS, 344, 761
O'Meara, J. M., Tytler, D., Kirkman, D., Suzuki, N., Prochaska, J. X., Lubin, D., & Wolfe, A. M. 2001, ApJ, 552, 718
Ostriker, J. P., & Steinhardt, P. J. 1995, Nature, 377, 600
Ozer, M., & Taha, O. 1987, Nucl. Phys. B, 287, 776
Perlmutter, S., et al. 1999, ApJ, 517, 565
Phillips, M. M., Lira, P., Suntzeff, N. B., Schommer, R. A., Hamuy, M., & Maza, J. 1999, AJ, 118, 1766
Podariu, S., & Ratra, B. 2001, ApJ, 563, 28
Randall, L. 2002, Science, 296, 1422
Randall, L., & Sundrum, R. 1999a, Phys. Rev. Lett., 83, 3370
———. 1999b, Phys. Rev. Lett., 83, 4690
Ratra, B., & Peebles, P. J. E. 1988, Phys. Rev. D, 37, 3406
Riess, A. G., et al. 1998, AJ, 116, 1009
———. 2004, ApJ, 607, 665
Sasaki, S. 1996, PASJ, 48, L119
Sen, A. A., & Sen, S. 2003, ApJ, 588, 1
Silva, P. T., & Bertolami, O. 2003, ApJ, 599, 829
Tegmark, M., et al. 2004a, Phys. Rev. D, 69, 103501
———. 2004b, ApJ, 606, 702
Tonry, J. L., et al. 2003, ApJ, 594, 1
Turner, M. S. 2002, ApJ, 576, L101
Turner, M. S., & Riess, A. G. 2002, ApJ, 569, 18
Turner, M. S., & White, M. 1997, Phys. Rev. D, 56, R4439
Vauclair, S. C., et al. 2003, A&A, 412, L37
Vishwakarma, R. G. 2001, Classical Quantum Gravity, 18, 1159
Wang, B., Gong, Y., & Su, R.-K. 2004, preprint (hep-th/0408032)
Wang, Y. 2000, ApJ, 536, 531
Wang, Y., Freese, K., Gondolo, P., & Lewis, M. 2003, ApJ, 594, 25
Wang, Y., & Garnavich, P. 2001, ApJ, 552, 445
Wang, Y., & Lovelace, G. 2001, ApJ, 562, L115
Weller, J., & Albrecht, A. 2002, Phys. Rev. D, 65, 103512
White, S. D. M., Navarro, J. F., Evrard, A. E., & Frenk, C. S. 1993, Nature, 366, 429
Zhu, Z.-H. 1998, A&A, 338, 777
Zhu, Z.-H., & Fujimoto, M.-K. 2002, ApJ, 581, 1
———. 2003, ApJ, 585, 52
———. 2004, ApJ, 602, 12
Zhu, Z.-H., Fujimoto, M.-K., & Tatsumi, D. 2001, A&A, 372, 377