Testing the local-void alternative to dark energy using galaxy pairs

F. Y. Wang * and Z. G. Dai†
School of Astronomy and Space Science, Nanjing University, Nanjing 210093, China
Key laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, Nanjing 210093, China

ABSTRACT
The possibility that we live in a special place in the universe, close to the center of a large, radially inhomogeneous void, has attracted attention recently as an alternative to dark energy or modified gravity to explain the accelerating universe. We show that the distribution of orientations of galaxy pairs can be used to test the Copernican principle that we are not in a central or special region of Universe. The popular void models cannot fit both the latest type Ia supernova, cosmic microwave background data and the distribution of orientations of galaxy pairs simultaneously. Our results rule out the void models at the 4σ confidence level as the origin of cosmic acceleration and favor the Copernican principle.

Key words: cosmology: theory - dark energy

1 INTRODUCTION
The standard model of cosmology based on the cosmological principle (homogeneity, isotropy, validity of General Relativity) which contains about 23% dark matter, 4% ordinary matter and 73% dark energy driving the acceleration of a flat universe has been established. Many astronomical observations support this standard picture, including type Ia supernovae (SNe Ia) (Riess et al. 1998; Perlmutter et al. 1999), cosmic microwave background (CMB) (Komatsu et al. 2011; Sherwin et al. 2011), baryon acoustic oscillations (BAO) (Eisenstein et al. 2005) and gamma-ray bursts (Dai et al. 2004; Wang et al. 2007; 2011).

In the meanwhile, inhomogeneous Lemaître-Tolman-Bondi (LTB) (Lemaître 1933; Tolman 1934; Bondi 1947) universe could also induce an apparent dimming of the light of distant supernovae. The idea is to drop the dark energy and the Copernican principle, and instead suppose that we are near the center of a large, nonlinearly underdense, nearly spherical void surrounded by a flat, matter dominated Einstein-de Sitter (EdS) spacetime. Because the observer must be at the center of void, so the LTB models violate the Copernican principle. Because of the observed isotropy of the CMB, the observer must be located very close to the center of the void (Ailes & Amarzguioui 2006). It was demonstrated LTB models can fit the SNe Ia data, as well as the BAO data and the CMB data (Garcia-Bellido & Haugboelle 2009). Some tests have actually been proposed: the Goodman-Caldwell-Stebbins test, which looks at the CMB inside our past lightcone (Goodman 1995; Caldwell & Stebbins 2008), the curvature test, which is based on the tight relation between curvature and expansion history in a Friedmann spacetime (Clarkson et al. 2008), and the radial and transverse BAO scale (Zibin et al. 2008; Garcia-Bellido & Haugboelle 2009). However, based on these tests, void models have not yet been ruled out (Clifton et al. 2008; Uzan et al. 2008; Biswas et al. 2010; Wang & Zhang 2012; Nadathur & Sarkar 2011). Zhang & Stebbins (2011) have excluded the Hubble bubble model as the possibility of cosmic acceleration using the the Compton-y distortion. Zibin & Moss (2011) also concluded that a very large class of void models was ruled out using this method. Here we propose a powerful tool, the orientations of galaxy pairs to test the Copernican principle.

The Alcock-Paczynski (AP) test is a purely geometric test of the expansion of the Universe (Alcock & Paczynski 1979). Marinoni & Buzzi (2010) implemented the AP test with the distribution of orientations of galaxy pairs in orbit around each other in binary systems. The principle of this method is that the orientations is thought to be completely random, with all orientations being equally likely if measured assuming a cosmology that matches the true underlying cosmology of the Universe in a Friedmann-Lemaître-Robertson-Walker (FLRW) universe after the effect of peculiar motion is excluded.

In this paper, we implement the Alcock-Paczynski test with pairs of galaxies to test the Copernican principle. The void models cannot both fit SNe Ia plus CMB data and orientations of galaxy pairs. Our results exclude the possibility
of the void models as the source of cosmic accelerating expansion and favor the Copernican principle.

2 THE VOID MODEL

We model the void as an isotropic, radially inhomogeneous universe described by the LTB metric,

\[ ds^2 = -c^2 dt^2 + \frac{A^2(r, t)}{1 + k(r)} dr^2 + A^2(r, t) d\Omega^2, \]

where a prime denotes the partial derivative with respect to the coordinate distance \( r \), and the curvature \( k(r) \) is a free function representing the local curvature. The transverse expansion rate is defined as \( H_A \equiv A(r, t)/A(r, t) \) and the radial expansion rate is defined as \( H_r \equiv A'(r, t)/A(r, t) \), where an overdot denotes the partial derivative with respect to \( t \).

The Friedmann equation in LTB metric is \( H^2 = F(r)/A^4(r, t) + c^2 k(r)/A^2(r, t) \), where \( F(r) > 0 \) is a free function which determines the local energy density. The dimensionless density parameters can be determined as \( \Omega_M(r) \) and \( \Omega_K \) by \( F(r) = H^2_0(r)\Omega_M(r)A_0^2(r) \) and \( c^2 k = H^2_0(r)\Omega_K(r)A_0^2(r) \), where \( H_0 \) and \( A_0 \) are the values of \( H(z, t) \) and \( A(r, t) \) respectively at the present time \( t = t_0 \).

So we can rewrite Friedmann equation in LTB metric as \( H^2_0 = H^2_0(r, t)\Omega_M(A_0/A)^3 + \Omega_K(r)(A_0/A)^2 \). This equation can be integrated from the time of the Big Bang, \( t_B = t_0(r) \), to yield the age of the universe at any given \((r, t)\),

\[ t_0 - t_0(r) = -\frac{1}{H_0(r)} \int_0^{A/A_0} \frac{dx}{\sqrt{\Omega_M(r)x^{-1} + \Omega_K(r)}}. \]

The function, \( A_0(r) \), corresponds to a gauge mode and we choose to set \( A_0(r) = r \). As stressed by Silk (1977) and Zibin (2008), it is crucial to consider only voids with vanishing decaying mode, so we set \( t_B(r) = 0 \) everywhere. Although Biswas et al (2010) have shown that the void models were better in agreement with observations if the void has been generated sometime in the early universe. Null radial geodesics described by

\[ \frac{dt}{dz} = -\frac{1}{(1 + z)H(z)} \frac{dr}{dz} = \frac{c\sqrt{1 + k(r)}}{(1 + z)A'(z)H(z)}. \]

where \( H(z) = H_0(r(z), t(z)) \). The angular diameter distance and luminosity distance are given by

\[ d_A(z) = A(r(z), t(z)), d_L(z) = (1 + z)^2 A(r(z), t(z)). \]

We will adopt the two parameterizations of the void profile \( \Omega_M(r) \). The first one is the constrained GBH model (Garcia-Bellido & Haugboelle 2008)

\[ \Omega_M(r) = \Omega_{M, \text{out}} + (\Omega_{M, \text{in}} - \Omega_{M, \text{out}}) \frac{1 - \tanh(r - r_0/2\Delta r)}{1 + \tanh(r_0/2\Delta r)}, \]

where the parameters \( r_0 \) and \( \Delta r \) characterize size and steepness of the density profile respectively. We wish to look only at voids that are asymptotically EdS, so we set \( \Omega_{M, \text{out}} = 1 \). We also set \( \Delta r = 0.35r_0 \), because this value can well fit the SNe Ia data (Garcia-Bellido & Haugboelle 2008; Marra & Paakkonen 2010). This density shape of GBH model can also contain other observations, such as CMB and BAO. The second one is a simple Gaussian form,

\[ \Omega_M(r) = \Omega_{M, \text{out}} + (\Omega_{M, \text{in}} - \Omega_{M, \text{out}}) \frac{1 - e^{-r^2/r_0^2}}{1 + e^{-r^2/r_0^2}}. \]

3 CONSTRAINT FROM SNE IA, CMB AND PAIRS OF GALAXIES

We use the recent Union2 SNe Compilation (Amanullah et al. 2010), which consists 557 SNe Ia in the redshift range \( z = 0.015 - 1.4 \). With \( d_L \) in units of megaparsecs, the predicted distance modulus is \( \mu(z) = 5 \log d_L(z) + 25 \). The likelihood analysis is based on the \( \chi^2 \) function:

\[ \chi^2_{SNe} = \sum_{i=1}^{557} \frac{[\mu_i - \mu_{\text{obs}}(z_i)]^2}{\sigma_i^2}. \]

We also use positions and amplitudes of peaks and troughs in the CMB spectrum to test the LTB models. The location of peaks and troughs can be calculated as Hu et al. (2001): \( l_m = (m - \phi_m) l_A \), where \( l_A = \pi \frac{d_A(z)^2}{r_s^2} \), \( d_A(z) \) is the angular diameter distance with the sound horizon of \( r_s \) at the recombination redshift of \( z^* \). We use the method of Marra & Paakkonen (2010) to calculated these values. We consider the position of the first, second, third
peak and of the first trough. We compute the corresponding phases \( \phi_1, \phi_{1.5}, \phi_2 \) and \( \phi_3 \) using the accurate analytical fits of Doran & Lilley (2002). The relative heights of second and third peak relative to the first one, \( H_2 \) and \( H_3 \) are also considered, for which we can use the fits of Hu et al. (2001).

So the \( \chi^2_{\text{CMB}} \) is (Marra & Paakkonen 2010)

\[
\chi^2_{\text{CMB}} = \sum_{1, 1.5, 2, 3} \frac{(l_m - l_m(W7))^2}{\sigma^2_{l_m}} + \sum_{2, 3} \frac{(H_1 - H_{1,W7})^2}{\sigma^2_{H_1}},
\]

where the W7 represents the best-fit WMAP7 spectrum (Jarosik et al. 2011).

Pairs of galaxies should be distributed with random orientations if the fundamental assumptions of homogeneity and isotropy are correct. But two factors affect this simple cosmology test. First, peculiar velocities displace the position of a galaxy along the line of sight from its true position. Marinoni and Buzzi modelled the peculiar velocity distortion as a Doppler shift where the observed line of sight separation is related to the actual separation. Second, an observer needs to assume a cosmological model to convert observed angles and redshifts into comoving distances. The uniform distribution of orientations is distorted if a wrong underlying cosmology of the Universe is assumed.

In a non-flat \( \Lambda \)CDM universe, the tilting angle \( \theta \) subtended between galaxy pairs and the line of sight, can be written as

\[
\sin^2 t = \{ 1 + |C_k(\chi_A)\cos \theta - \frac{S_k(\chi_A)C_k(\chi_B)}{S_k(\chi_B)\sin \theta}|^2 \}^{-1},
\]

for details, see Marinoni et al. (2012). It is nontrivial to calculate the tilting angle and average anisotropy of pairs in LTB models. The measured galaxy (matter) clustering and its evolution agree with the standard \( \Lambda \)CDM cosmology to a factor of about 2 uncertainty up to \( z \approx 1 \) (Tegmark et al. 2004; Coil et al. 2006; Fu et al. 2008; Schrabback et al. 2010; Guzzo et al. 2008). A minimalist approach is to simply use the \( \Lambda \)CDM value since any viable LTB models must be consistent with these data. So we use the observed average anisotropy of pairs from Marinoni & Buzzi (2010) derived in \( \Lambda \)CDM cosmology. Zhang & Stebbings (2011) also approximated the matter power spectrum by its form in a standard \( \Lambda \)CDM cosmology. The observed tilting angle is shifted to apparent angle \( \tau \) because of the geometric distortions induced by the peculiar velocities of the pair’s members. The probability distribution function of the apparent angle \( \tau \) which is given by Marinoni & Buzzi (2010)

\[
\Psi(\tau)d\tau = \frac{1}{2} \frac{(1 + \sigma^2)(1 + \tan^2 \tau)}{[1 + (1 + \sigma^2) \tan^2 \tau]^{3/2}} |\tan \tau| d\tau,
\]

and the parameter \( \sigma \) depends on the cosmological expansion history as

\[
\sigma(z) = \alpha \frac{H_0(r)(1 + z)}{H_1(r, t)}.
\]

The normalization parameter \( \alpha \) is given by \( \alpha = H_1^{-1} (\langle \frac{dv_z^2}{dr^2} \rangle)^{1/2} \). Because in the LTB metric, the transverse and radial expansion rates are different, so the correct value must be used in our calculations. When we use the galaxy pairs for AP test, the velocity perturbation \( \sigma \) used in equation (12) is related to the peculiar motions of the pair members along the line of sight. So we use radial expansion rate \( H_1 \) to calculate the velocity perturbation. Because the AP test is similar to BAO, we can see this formula is also similar to the redshift interval \( \delta z \) corresponding to the acoustic scale in the radial direction (García-Bellido & Haugboelle 2008; Biswas et al. 2010; Marra & Paakkonen 2010). In the homogeneous \( \Lambda \)CDM model, Marinoni & Buzzi (2010) used the normal expansion rate \( H(z) \). Marinoni & Buzzi (2010) derived the distribution \( \Psi(\tau) \) as the average anisotropy of pair (AAP), which is given by

\[
\mu_\alpha = \int \sin^2 \tau \Psi(\tau) d\tau = \frac{(1 + \sigma^2) \arctan(\sigma) - \sigma}{\sigma^3}.
\]

At \( z \approx 0 \), Marinoni & Buzzi (2010) obtained \( \alpha = 5.79^{+0.32}_{-0.35} \), using binaries in the seventh data release of the Sloan Digital Sky Survey (SDSS) (Abazajian et al. 2009). The normalization factor \( \alpha \) is assumed to be constant for all redshifts and for different galaxy selections (Marinoni & Buzzi 2010). Although Jennings et al. (2012) found that the value of \( \alpha \) could have a small variation with cosmology and redshift, Marinoni & Buzzi established that the changes of best fit value cannot exceed the 1σ confidence level if the variation of \( \alpha \) is less than 10%. So this assumption could be reasonable. Bellomo et al. (2012) also found that observations of close-pairs of galaxies do show promise for AP cosmological measurements, especially for low mass, isolated galaxies. The high-redshift (up to \( z \approx 1.45 \)) AAP are obtained using the third data release of the DEEP2 survey (Davis et al. 2007). The value of \( \chi^2_{\text{AAP}} \) is

\[
\chi^2_{\text{AAP}} = \sum_{i=1}^{9} \frac{[\mu_\alpha - \mu_{\alpha,\text{obs}}(z_i)]^2}{\sigma^2_{\alpha, i}},
\]

We adopt the value of \( \mu_{\alpha, \text{obs}} \) and \( \sigma_{\alpha, \text{obs}} \) from Fig. 2 of Marinoni & Buzzi (2010), which are shown as points in the Fig. 3.
\[ \chi_{dV^2}^2 = \sum_{i=1}^{9} \frac{|\langle dV^2_i(z_i) \rangle - \langle dV^2(z_i) \rangle|^2}{\sigma_{dV^2}^2}. \]  

We use the value of \( \langle dV^2(x) \rangle \) and \( \sigma_{dV^2} \) from Fig. (5S) of Marinoni & Buzzi (2010). The total \( \chi_{\text{AAP}}^2 \) is

\[ \chi_{\text{AAP}}^2 = \chi_{\text{AAP}}^2 + \chi_{dV^2}^2. \]

In Fig. 1 we show the 1σ, 2σ and 3σ contours in the \( \Omega_{M,\text{in}} - r_0 \) plane for the constrained GBH model. In the calculation, the priors from WMAP7, such as the age of Universe \( t_0 = 13.79 \text{ Gy} \) and spectral index \( n_s = 0.96 \) are used (Komatsu, et al. 2011). We also marginalize the Hubble constant \( H_0 \) in the range \( 50 \leq H_0 \leq 80 \text{ km s}^{-1}\text{Mpc}^{-1} \). The constraint from SNe Ia and CMB is shown as dash-dot contours, and dashed contours for AAP. The allowed range of \( r_0 \) is 1.80 Gpc < \( r_0 \) < 4.10 Gpc at 3σ level from SNe Ia+CMB. But the allowed range of \( r_0 \) is \( r_0 > 4.42 \) Gpc at 3σ level from AAP. These two contours do not overlap. So the constrained GBH model can not explain the observations of SNe Ia+CMB and AAP. The solid contours are derived from SNe Ia+CMB+AAP with \( \chi_{\text{min}} = 641.40 \). While for the \( \Lambda \)CDM model, the minimum \( \chi^2 \) is 620.37. The constrained GBH model is excluded at the 4σ confidence level compared to \( \Lambda \)CDM. In Fig. 2 we show the 1σ, 2σ and 3σ contours in the \( \Omega_{M,\text{in}} - r_0 \) plane for the gaussian LTB model. The solid contours are derived from SNe Ia+CMB+AAP with \( \chi_{\text{min}} = 646.50 \). This model is also excluded at the 4σ confidence level compared to \( \Lambda \)CDM. From the \( \chi^2_{\text{min}} \) of the two void models, we conclude that the precise form of the density profile may not be essential. Because the void models depend crucially on the void depth \( \delta_2 = (\Omega_{M,\text{in}} - \Omega_{M,\text{out}})/\Omega_{M,\text{out}} \) and the void size \( r_0 \). So our conclusion is almost independent of void model.

In Fig. 3 we show the theoretical redshift scaling of the AAP in these two LTB models. In the up panel, we use the best fit parameters from SNe Ia+CMB for the constrained GBH model, \( r_0 = 3.0 \) Gpc and \( \Omega_{M,\text{in}} = 0.10 \). Obviously, the predicted values of AAP deviate from theobservational values at high redshift. The \( \chi^2 \) value is 37.35 for these nine data points. In the bottom panel, \( r_0 = 3.6 \) Gpc and \( \Omega_{M,\text{in}} = 0.12 \) are used for the Gaussian LTB model. The \( \chi^2 \) value is 41.96 for these nine data points.

We must note that the local Hubble constant \( H_{\text{loc}} \) is also a big obstacle to the void models. Because the measurement of the Hubble constant is carried out mostly within a distance of roughly \( r_{\text{loc}} \sim 200 \) Mpc (Riess et al. 2011; Freedman et al. 2012), we obtain the \( H_{\text{loc}} \) (Marra & Paakkonen 2010)

\[ H_{\text{loc}} = \int_0^{r_{\text{loc}}} H_0(r)4\pi r^2 dr/(4\pi/3r_{\text{loc}}^3). \]

In order to fit both the SNe Ia and CMB, the value of \( H_{\text{loc}} \) is 64±3.2 km s\(^{-1}\)Mpc\(^{-1}\) in the constrained GBH model or 63±3.5 km s\(^{-1}\)Mpc\(^{-1}\) in the Gaussian LTB model. Riess et al. (2011) determined the Hubble constant with 3% uncertainty as 73.8±2.4 km s\(^{-1}\)Mpc\(^{-1}\). Freedman et al. (2012) measured the Hubble constant as 74.3 ± 2.1 km s\(^{-1}\)Mpc\(^{-1}\).
ACKNOWLEDGMENTS

We thank an anonymous referee for helpful comments and suggestions. We have benefited from reading the publicly available code of Marra & Paakkonen (2010). This work is supported by the National Natural Science Foundation of China (grants 11103007 and 11033002).

REFERENCES

Abazajian K. N., et al., 2009, ApJS, 182, 543
Alcock C., Paczynski B., 1979, Nature, 281, 358
Alnes H., Amarzguioui M., 2006, PRD, 74, 103520
Amanullah R., et al., 2010, ApJ, 716, 712
Belloso A. B., et al., 2012, PRD, 86, 023530
Biswas T., Notari A., Valkenburg W., 2010, JCAP, 11, 030
Bondi H., 1947, MNRAS, 107, 410
Bull P., Clifton T., 2012, PRD, 85, 103512
Caldwell R. R., Stebbins A., 2008, PRL, 100, 191302
Clarkson C., Bassett B., Lu T. H.-C., 2008, PRL, 101, 011301
Clarkson C., Regis M., 2011, JCAP, 02, 013
Clifton V. T., Ferreira P. G., Land K., 2008, PRL, 101, 131302
Coil A. L., et al., 2006, ApJ, 644, 671
Dai Z. G., Liang E. W., Xu. D., 2004, ApJ, 612, L101
Davis M., et al., 2007, ApJ, 660, 1
Doran M., Lilley M., 2002, MNRAS, 330, 965
Eisenstein D. J. et. al., 2005, ApJ, 633, 560
Februrary S., et al., 2010, MNRAS, 405, 2231
Freedman W. L., et al., 2012, ApJ, 758, 24
Fu L. et al., 2008, A&A, 479, 9
Garcia-Bellido J., Haugboelle T., 2008, JCAP, 04, 003
Garcia-Bellido J., Haugboelle T., 2009, JCAP, 09, 028
Goodman J., 1995, PRD, 52, 1821
Guzzo L. et al., 2008, Nature, 451, 541
Hu W., Fukugita M., Zaldarriaga M., Tegmark M., 2001, ApJ, 549, 669
Jarosik N., et al., 2011, ApJS, 192, 14
Jennings E., Baugh C. M., Pascoli S., 2012, MNRAS, 420, 1079
Komatsu E. et. al., 2011, ApJS, 192, 18
Lemaître G., 1933, Ann. Soc. Sci. Brussels. A53, 51
Marinoni C., Buzzi A., 2010, Nature, 468, 539
Marinoni C., Bel J., Buzzi A., 2012, JCAP, 10, 036
Marra V., Paakkonen M., 2010, JCAP, 12, 021
Nadathur S., Sarkar S., 2011, PRD, 83, 063506
Perlmutter S. et al., 1999, ApJ, 517, 565
Riess A. et al., 1998, AJ, 116, 1009
Riess A. G., et al., 2011, ApJ, 730, 119
Schlegel D., et al., arXiv:1106.1706
Schrabback T. et al., 2010, A&A, 516, A63
Sherwin B. D., et. al., 2011, PRL, 107, 021302
Silk J., 1977, A&A, 59, 53
Tegmark M., et al., 2004, ApJ, 606, 702
Tolman R. C., 1934, PNAS, 20, 169
Uzan J. P., Clarkson C., Ellis G. F. R., 2008, PRL, 100, 191303
Wang F. Y., Dai, Z. G., Zhu, Z. H., 2007, ApJ, 667, 1
Wang F. Y., Qi S., Dai Z. G., 2011, MNRAS, 415, 3423
Wang H., Zhang T. J., 2012, ApJ, 748, 111

Zhang P. J., Stebbins A., 2011, PRL, 107, 041301
Zibin J. P., 2008, PRD, 78, 043504
Zibin J. P., Moss A., 2011, Class. Quantum Grav., 28, 164005
Zibin J. P., Moss A., Scott D., 2008, PRL, 101, 251303