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DETECTION OF THE EFFECT OF COSMOLOGICAL LARGE-SCALE STRUCTURE ON THE ORIENTATION OF GALAXIES

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ABSTRACT

Galaxies are not distributed randomly throughout space but are instead arranged in an intricate "cosmic web" of filaments and walls surrounding bubble-like voids. There is still no compelling observational evidence of a link between the structure of the cosmic web and how galaxies form within it. However, such a connection is expected on the basis of our understanding of the origin of galaxy angular momentum: disk galaxies should be highly inclined relative to the plane defined by the large-scale structure surrounding them. Using the two largest galaxy redshift surveys currently in existence (2dFGRS and SDSS), we show at the 99.7% confidence level that these alignments do indeed exist: spiral galaxies located on the shells of the largest cosmic voids have rotation axes that lie preferentially on the void surface.

Subject headings: dark matter — galaxies: halos — galaxies: spiral — galaxies: structure — large-scale structure of universe — methods: statistical

1. INTRODUCTION

The spin of spiral galaxies is believed to be generated by tidal torques operating in the early universe on the primordial material destined to form a galaxy (Peebles 1969; White 1984). A generic prediction of this theory is the existence of local correlations between galaxy rotation axes and the surrounding matter field (Barnes & Efstathiou 1987; Porciani et al. 2002a, 2002b; Navarro et al. 2004, hereafter NAS04). Several observational studies (Helou & Salpeter 1982; Flin & Godłowski 1986; Garrido et al. 1993; NAS04) have looked for a preferential spatial orientation (or alignment) of galaxy rotation axes with respect to their surrounding large-scale structures. These attempts have been focused on galaxies in the vicinity of the Milky Way. Our Galaxy and its neighbors are embedded in a slab, the supergalactic plane (de Vaucouleurs 1953), that extends out to several tens of megaparsecs from our Galaxy. Prior work has concentrated on detecting an excess of nearby galaxies whose rotation axes were approximately perpendicular to the normal to the supergalactic plane. The existence of such an alignment has been difficult to establish, with claims of detection but also claims of no convincing evidence for alignments (Dekel 1985).

A number of factors complicate the above analysis. For example, the direction of the rotation axis of a spiral galaxy requires knowledge of not only the position angle and inclination, but also which side of the galaxy is closer to the observer. This latter information is known only for the closest galaxies to our own. This uncertainty, however, can be avoided if only edge-on or face-on galaxies are selected (NAS04). In this case, the spatial orientation of the rotation axis lies in the sky plane (edge-on case) or points exactly toward or away from us (face-on case). Nevertheless, this approach has the disadvantage that it significantly reduces the sample size. A natural solution would be to explore the orientation of edge-on and face-on spiral galaxies in two-dimensional large-scale distributions of galaxies beyond the supergalactic plane.

To explore the alignment of the galaxies with respect to their surrounding matter, it is necessary to characterize the spatial orientation of the cosmic sheet (or plane) at the position of the galaxy. This can be done by estimating the direction of the minor axis of the sheet at that point. This minor axis is, however, very difficult to measure in practice because of redshift-space distortion: peculiar velocities not associated with the Hubble flow that prevent us from deriving the true three-dimensional arrangement of the galaxies. Consequently, the detection and characterization of large-scale sheetlike distributions of galaxies in the redshift space is ill-defined. In this Letter, we present an alternative way of exploring preferential spatial orientations without resorting to the detection of planes. We concentrate our analysis on galaxies located on the shells of the largest cosmic voids ($r_{\rm void} > 10\ h^{-1}$ Mpc). We adopt a cosmological model with $H_0 = 100\ h$ km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

2. VOID-BASED METHOD AND SAMPLE SELECTION

The gradient of the density field, $\boldsymbol{g}$, at points around large voids shows a strong tendency to be aligned with the direction of the vector going from the center of the void to those points. So, any departure from isotropy of the distribution of the angle between the galaxy plane and the local "sheet" will be inherited by the distribution of the angle θ between the galaxy "spin" $\boldsymbol{s}$ and the vector joining the galaxy with the center of the corresponding void $\boldsymbol{r}$ (Fig. 1). Thus, θ can be easily determined as

$$\theta = \arccos\left(\frac{\boldsymbol{s}\cdot\boldsymbol{r}}{|\boldsymbol{s}|\,|\boldsymbol{r}|}\right). \tag{1}$$

When the galaxy lies in the shell of a large void, the vector $\boldsymbol{g}$ can be approximated by the vector $\boldsymbol{r}$ joining the center of the void to the center of the galaxy. If the position of the void center is $\boldsymbol{r}_{\rm void}$ and the position vector of the galaxy is $\boldsymbol{r}_{\rm galaxy}$, then $\boldsymbol{r}$ is simply $\boldsymbol{r} = \boldsymbol{r}_{\rm galaxy} - \boldsymbol{r}_{\rm void}$. To evaluate the spin vector $\boldsymbol{s}$ of a galaxy, we need to know its position angle ϕ, its semiminor-to-semimajor axis ratio b/a, and its coordinates (α, δ). We define the inclination angle as $\zeta = \arcsin(b/a)$.

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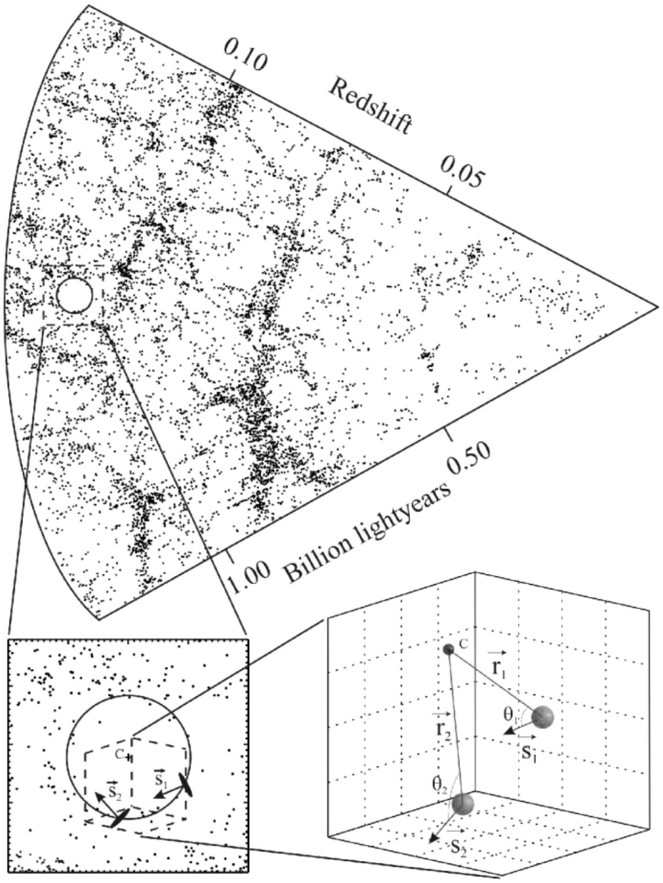

FIG. 1.—Schematic representation of the technique used to measure the angle θ between the spin axis of a galaxy $\boldsymbol{s}_i$ and the orientation vector of the surrounding material. Large voids are detected in the cosmic web. We search for edge-on or face-on galaxies within the shells surrounding the voids. Because we select large voids, $\boldsymbol{r}_i$ (the vector joining the center of the void to the center of the galaxy) is a good approximation to the vector normal to the shell of the void at the galaxy's position. Finally, the angle θ between the above vectors is computed.

In our definition, ϕ increases counterclockwise from north to east in the plane of the sky. So, if we consider a galaxy characterized by angles $(\alpha, \delta, \phi, \zeta) = (0, 0, 0, 0)$ (i.e., an edge-on galaxy along the z-axis), the spin of this galaxy should be $\boldsymbol{s}_0 = (0, 1, 0)$. Therefore, the spin $\boldsymbol{s}$ of a generic galaxy can be computed as the product $\boldsymbol{s} = \mathbf{M}(\alpha, \delta, \phi, \zeta)\boldsymbol{s}_0$, where $\mathbf{M}(\alpha, \delta, \phi, \zeta)$ is the transformation matrix that considers all the rotations for the four angles. If we denote by $\mathbf{R}_q(\phi)$ the matrix for a rotation of angle ϕ around the axis q, then we have $\mathbf{M}(\alpha, \delta, \phi, \zeta) = \mathbf{R}_z(-\alpha)\mathbf{R}_y(-\delta)\mathbf{R}_x(\phi)\mathbf{R}_z(\zeta)$. Introducing the explicit expressions for the rotation matrices and substituting the value of $\mathbf{M}$, we find

$$s_x = \cos\alpha\cos\delta\sin\zeta + \cos\zeta\,(\sin\phi\cos\alpha\sin\delta - \cos\phi\sin\alpha), \tag{2}$$

$$s_y = \sin\alpha\cos\delta\sin\zeta + \cos\zeta\,(\sin\phi\sin\alpha\sin\delta + \cos\phi\cos\alpha), \tag{3}$$

$$s_z = \sin\delta\sin\zeta - \cos\zeta\sin\phi\cos\delta. \tag{4}$$

The above set of equations together with $\boldsymbol{r}$ gives us all the information necessary to evaluate θ. However, it is worth noting that in the determination of ζ, the two-valued arcsine provides us with two values for the inclination angle: $\pm\zeta$ (i.e., we are not able to decide whether the spin is pointing toward us or away from us). To avoid this problem, we had to constrain our analysis to edge-on (or face-on) galaxies, that is, those with $\zeta \sim 0°$ (or $\zeta \sim 90°$). In practice, our sample considered galaxies with $b/a \leq 0.208$ (or $b/a \geq 0.978$), which implies that $\zeta \leq 12°$ (or $\zeta \geq 78°$).

To achieve a sizable sample of large voids, we have used the Two Degree Field Galaxy Redshift Survey (2dFGRS; Colless et al. 2001) and the Sloan Digital Sky Survey (SDSS; York et al. 2000). To characterize the uncertainty in the angle θ, we have used "mock" 2dF and SDSS galaxy redshift surveys constructed from a set of large, high-resolution cosmological N-body simulations (Cole et al. 1998). These simulations do not resolve detail on the scale of a galaxy, so we have assumed for this test that all the galaxies were edge-on with the position angle of the rotation axis uniformly distributed in the sky plane. We measured the difference between the angles θ estimated in real space and in redshift space. We find that this difference is well described by a Gaussian distribution with standard deviation of 10°. In addition, these simulations allow us to estimate the uncertainty in measuring the center position of the voids as $\pm 2.5\ h^{-1}$ Mpc. This uncertainty is smaller than the uncertainty in estimating the position for individual galaxies, $\pm 4.2\ h^{-1}$ Mpc, because the central position of the void is determined using a large number of galaxies in the shell.

The 2dFGRS and SDSS (Data Release 3) catalogs give photometric and spectroscopic information for hundreds of thousands of galaxies. The 90% redshift completeness limit of the 2dFGRS is reached at $b_\mathrm{J} = 19$ mag, and that of SDSS is reached at $b_\mathrm{J} = 18.8$ mag (Norberg et al. 2002). If we wish to maximize the volume and the number of galaxies under exploration, the above magnitude limits imply that we must estimate the central position of the voids using all galaxies brighter than $M_{b_\mathrm{J}} = -19.32 + 5\log h$ with $z < 0.14$ in the 2dFGRS and $z < 0.13$ in the SDSS. The number of voids that we detect with radius larger than 10 h^{-1} Mpc is 239 (2dFGRS) and 756 (SDSS). The detection and size estimation of the voids was performed with the "HB" void finder (Patiri et al. 2006).

Once the largest voids are obtained, we select all the edge-on and face-on galaxies within shells $r_\mathrm{void} < r < r_\mathrm{void} + 4\ h^{-1}$ Mpc surrounding the voids. As mentioned above, we consider a spiral galaxy to be edge-on if the ratio of semiminor to semimajor axis is less than 0.208. This restriction removes spheroidal galaxies from our sample but leaves a small residue from close galaxy pairs, which was eliminated by checking all the galaxies individually by visual inspection. Face-on galaxies are selected if the ratio of semiminor to semimajor axis is greater than 0.978. The face-on–selected sample is contaminated by round spheroidal galaxies, which are removed by visual inspection. This last step can only be achieved in the SDSS, since the 2dFGRS lacks good-quality image resolution allowing the visual classification of the galaxies. Consequently, we only used edge-on galaxies in the 2dFGRS sample.

To avoid edge biasing in our results, we then removed all the above voids that did not satisfy the condition that their radii plus the radius of the shells are fully contained within the survey area. This leaves us with 149 (2dFGRS) and 321 (SDSS) voids. The number of voids that contain at least one edge-on or face-on spiral in their shells are 49 (2dFGRS) and 129 (SDSS). The final number of galaxies we analyze is 60 (edge-on; 2dFGRS), 118 (edge-on; SDSS), and 23 (face-on; SDSS). As expected from projection effects, the number of face-on

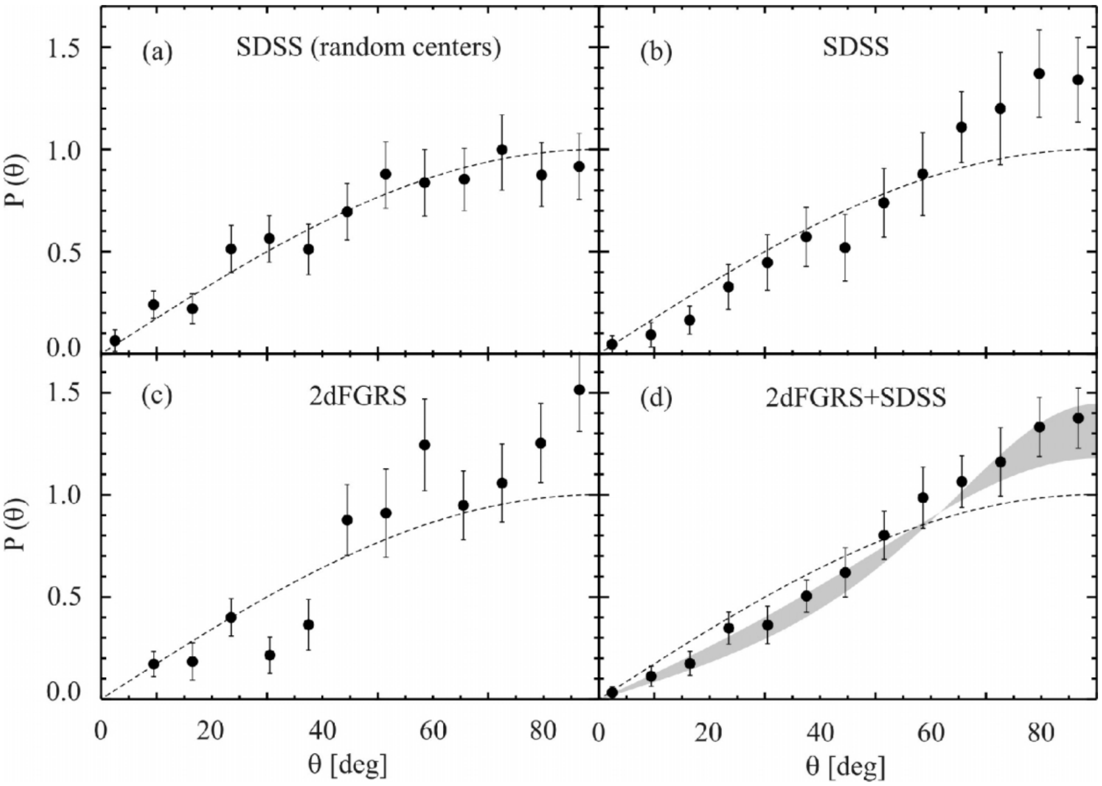

FIG. 2.—Probability density distribution of the angles θ between the rotation axes of the galaxies and the vectors normal to the planes defined by their surrounding matter. The error bars on each bin represent the standard deviation and are evaluated by means of 1000 Monte Carlo simulations in which the inclination of the galaxies is allowed to vary within a Gaussian distribution with σ equal to 6° (i.e., half the maximum angular inclination one of our galaxies could have within our edge-on selection criteria, under the assumption that galactic disks are infinitely thin). The error bars also include the Poisson error. The dashed lines represent the null hypothesis (i.e., a sine distribution). (*a*) Results from using random centers for the voids within the survey volume; (*b*, *c*) output when the centers of the large voids are used in SDSS and 2dFGRS; (*d*) angular distribution when the full data set is used. The gray region in (*d*) corresponds to Lee's analytic prediction (Lee 2004) for $c = 0.7^{+0.1}_{-0.2}$. The *c*-value is estimated by means of a χ^2 minimization.

galaxies is much smaller than the number of edge-on galaxies. The total number of objects in our sample is 201. For each of these galaxies, we derived the angle θ between the rotation axis and the local void wall orientation as explained above.

3. RESULTS AND DISCUSSION

The observed probability density distribution of the angles θ is shown in Figure 2. Figure 2*a* shows the result of a test placing the centers of the voids randomly within the survey volume. The number of edge-on galaxies and their distances to the centers of these voids are similar in this control experiment to the real case. As expected, no signal is detected. When using the centers of the real voids, both in the SDSS (Fig. 2*b*) and the 2dFGRS (Fig. 2*c*), the distribution follows a similar trend, although the distribution for the 2dFGRS is significantly noisier as a result of the smaller number of objects. The combined sample is shown in Figure 2*d*. The rotation axes of the galaxies tend to lie in the plane parallel to the surface of the void (i.e., the angles θ are predominantly large). We have used three different statistics to test the rejection of the null hypothesis (i.e., that the orientation of the galaxies is randomly distributed): the departure of the average (Avni & Bahcall 1980) of $\sin\theta$ from 0.5 (i.e., the expected value in the null hypothesis case), the Kolmogorov-Smirnov (K-S) test, and the χ^2 test. The three statistics agree in the rejection of the null hypothesis at the ~99.7% level ($\sin\theta$ test, 99.7%; K-S test, 99.6%; χ^2 test, 99.8%) when the full galaxy sample (Fig. 2*d*) is considered. For consistency with the 2dFGRS data, we have checked whether removing the face-on galaxies from the SDSS data affects our conclusion. As expected because of the small number of face-on galaxies, the signal only decreases very slightly (~0.1%) when these objects are removed, and the main conclusion (i.e., the rejection of the null hypothesis) remains unchanged.

In Figure 2*d*, we show a comparison of our results with Lee's recent analytic evaluation (Lee 2004) of galaxy inclinations within the framework of the tidal torque theory. The strength of the intrinsic galaxy alignment of the galaxies with local shears at the present epoch is expressed as the following quadratic relation:

$$\langle L_i L_j \rangle = \frac{1+c}{3}\delta_{ij} - c\hat{T}_{ik}\hat{T}_{kj}, \qquad (5)$$

(Lee & Pen 2002), where $\boldsymbol{L}$ is the galaxy spin vector, $\hat{\mathbf{T}}$ is the rescaled traceless shear tensor $\mathbf{T}$, defined as $\hat{T}_{ij} = \tilde{T}_{ij}/|\tilde{\mathbf{T}}|$ with $\tilde{T}_{ij} \equiv T_{ij} - \mathrm{Tr}\,(\mathbf{T})\,\delta_{ij}/3$, and c is a correlation parameter introduced to quantify the strength of the intrinsic shear-spin alignment in the range [0, 1]. The best agreement with the theory is obtained when Lee's correlation parameter c is $0.7^{+0.1}_{-0.2}$. When $c = 1$, the strength of the galaxy alignment with the large-scale distribution is maximum, whereas $c = 0$ implies that galaxies are oriented randomly. It is worth noting that the value of c measured in this work is a lower limit to the true value, because it has been evaluated without any attempt to correct for redshift distortion. Consequently, the strength (and statistical significance) of the observed alignment in true three-dimensional space should be higher.

Because of lack of resolution, with present-day *N*-body simulations what one can predict is the intrinsic alignment of underlying dark halos rather than that of the observable luminous parts of the galaxies. Although the standard theory of galaxy formation assumes that the rotation axes of the luminous parts align with those of the dark halos, recent hydrodynamic simulations imply that the luminous components could conserve the initial memory of the intrinsic shear-spin correlation better than the dark matter components (NAS04). Interestingly, our best-fit value of $c = 0.7$ is ≥ 2 times higher than that found in *N*-body simulations (Lee & Pen 2000; Lee et al. 2005). This reinforces the idea that the luminous parts of the galaxies tend to retain an initial memory of the surrounding matter better than their dark matter counterparts do.

Finally, the positive detection of alignments between galaxies and their surrounding matter shown in this work would explain one of the most intriguing galaxy properties: the tendency of satellite galaxies to avoid orbits that are coplanar with their host spiral galaxies (known as the “Holmberg effect”; Holmberg 1969; Zaritsky et al. 1997; Sales & Lambas 2004). As we have shown, the rotation axes of the galaxies preferentially lie on the sheets, and consequently, the satellite galaxies that are accreted through the filaments will populate mainly polar orbits.

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