TENTATIVE DETECTION OF GALAXY SPIN CORRELATIONS IN THE TULLY CATALOG

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ABSTRACT

We report a tentative detection of spin correlations in the Tully catalog of nearby galaxies. We define a simple but nontrivial spin correlation function and find an analytic estimate of it in the frame of the linear perturbation theory. Then we present the observed spin correlation signal from the Tully galaxies with error bars. The threedimensional spin correlation turns out to be significant at the 97% confidence level, detected out to a few h \(^{-1}\) Mpc. This observed correlation is consistent with the theoretical prediction based on the gravitational instability picture of galaxy formation. An analysis of systematic errors is also presented. The observed strength of correlation may be sufficient to significantly affect the blank field of weak-lensing searches.

Subject headings: galaxies: statistics — large-scale structure of universe

1. INTRODUCTION

Considerable effort has been devoted to the observational detection of any preferred direction in the orientation of galaxy spin vectors in the last century. Although several observational studies with various sample sizes and methods have reported the existence of some pattern of galaxy alignments (Strom & Strom 1978; Binggeli 1982; Flin 1988; Kashiwawa & Okamura 1992), there is no established evidence for significant preferential galaxy alignments yet (Dekel 1985; Hoffman et al. 1989; Han, Gould, & Sacket 1995; Cabanela & Dickey 1999). However, it has been recently pointed out that the sample size of galaxies in past efforts were too small to detect weak galaxy alignments unambiguously (Cabanela & Dickey 1999).

Theoretically, galaxy spin alignment is also an interesting issue since its existence has been predicted by the standard theory addressing the origin of galaxy spins. Very recently, intrinsic correlation of galaxy alignments has attracted considerable attention mainly because it could contribute a significant contaminant in blank fields of the statistical search for weak gravitational lensing (Catelan, Kamionkowski, & Blandford 2000; Heavens, Refregier, & Heymans 2000; Croft & Metzler 2000). In addition, detection of the intrinsic galaxy alignments by itself could have a fundamental impact on cosmology since it might shed light on the reconstruction of the initial density field through the galaxy spin field (Lee & Pen 2000a, hereafter LP00a). The goals of this Letter are (1) to estimate the strength of intrinsic galaxy spin correlations from a physical theory and (2) to measure the correlation signal directly from observed galaxies.

2. PHYSICAL ANALYSIS

In the gravitational instability picture of galaxy formation, the angular momentum of a galaxy originates from the local shear due to the protogalactic tidal interaction with the surrounding matter (Hoyle 1949; Peebles 1969). Using the first-order linear theory (White 1984; Catelan & Theuns 1996; its prediction on the galaxy spin axis has been shown to be quite valid even in a nonlinear regime by LP00a), LP00a have found a general quadratic expression for the expected unit galaxy spins given the intrinsic local shears: \( \langle \hat{L}(x) \cdot \hat{L}(x + r) \rangle = \eta \), where \( \eta \) is the value of \( \langle \hat{L}(x) \cdot \hat{L}(x) \rangle \) for the case of random spins; \( \eta = 1 \) for the three-dimensional spins, while \( \eta = \frac{2}{3} \) for the two-dimensional spins. Note that \( \langle \hat{L}(x) \cdot \hat{L}(x) \rangle = \langle \hat{L}(x) \hat{L}(x) \rangle = \frac{2}{3} \). Using only directional information, the correlation in angle is most readily measured this way. Since we do not measure the chirality of each galaxy’s rotation axis, the statistic must be symmetric under 180° rotation. Using \( \hat{L} \hat{L} = (1 + a) \delta_a/3 - a \hat{T}_a \hat{T}_a \), one can estimate

\[
\langle \hat{L}(x) \cdot \hat{L}(x) \rangle = \langle \hat{L}(x) \hat{L}(x) \rangle
\]

such that

\[
\langle \hat{L}_1 \hat{L}_2 \hat{L}_3 \rangle = \langle \hat{L}_1 \hat{L}_2 \hat{L}_3 \rangle
\]

\[
= \langle 1 + a \delta_a/3 - a \hat{T}_a \hat{T}_a \rangle \langle 1 + a \delta_a/3 - a \hat{T}_a \hat{T}_a \rangle
\]

\[
= \frac{1}{3} - a^2/3 + a^2 \langle \hat{T}_a \hat{T}_a \hat{T}_a \rangle.
\]
To calculate \( \langle \hat{T}_n \cdot \hat{T}_m \rangle \), we approximate the unit traceless shear tensor \( \hat{T} \) as a Gaussian variable of the traceless shear and apply the Wick theorem to derive

\[
\langle \hat{T}_n \cdot \hat{T}_m \rangle \approx \langle \hat{T}_n \rangle \langle \hat{T}_m \rangle + \langle \hat{T}_n \rangle \langle \hat{T}_m \rangle + \langle \hat{T}_n \rangle \langle \hat{T}_m \rangle = \frac{1}{3} + \xi (r)/6.
\]

Here \( \xi (r) \) is the correlation of the top-hat convolved density field normalized by \( \xi (0) = 1 \).

Hence, we finally have

\[ \eta (r) \approx A \xi (r), \]

with \( A = a^2/6 \) for the three-dimensional case. Note that this theoretical prediction has no free parameter and follows directly from first principles and an N-body normalization of the shear-spin correlation amplitude of \( a \). The approximation is made only when we apply the Wick theorem. In fact, we have verified in numerical realization of a Gaussian random field that the Wick expansion on \( \hat{T} \) approximates the true correlation within a few percent relative error. For the two-dimensional case, it can be shown with the same manner that \( A = 25a^2/96 \). For a detailed derivation of equation (1), see Appendix H in LP00b.

On galaxy scales, the power spectrum is well approximated by a power law, \( P(k) = k^n \) with \( n = -2 \), for which \( \xi (r) \sim r^{-4} \). Thus, equation (1) predicts that for neighboring galaxies (a few \( h^{-1} \) Mpc), the spin-spin correlation is of order 1%, decreasing rapidly as \( r^{-2} \). It will decrease more rapidly as one moves to larger scales. Thus, we expect negligible spin correlation signal at separations of more than a few \( h^{-1} \) Mpc.

3. OBSERVED SIGNAL

For this study, we use a subsample of 12,122 spiral galaxies from the Tully catalog (B. Tully 2000, private communication). The spiral galaxies are selected here as galaxies being type 0±9 from the Tully catalog (B. Tully 2000, private communication). The spiral galaxies are selected here as galaxies being type 0±9 from the Tully catalog (B. Tully 2000, private communication). The spiral galaxies are selected here as galaxies being type 0±9 from the Tully catalog (B. Tully 2000, private communication).

To calculate \( \eta (r) \approx A \xi (r) \), we rewrite \( \eta (r) \) as \( \eta (r) = \xi (r)/r \). The approximation is made only when we apply the Wick theorem. In fact, we have verified in numerical realization of a Gaussian random field that the Wick expansion on \( \hat{T} \) approximates the true correlation within a few percent relative error. For the two-dimensional case, it can be shown with the same manner that \( A = 25a^2/96 \). For a detailed derivation of equation (1), see Appendix H in LP00b.

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We redistribute the given \( \alpha \) and \( R \) uniformly according to their original order (\( R \) is redistributed within each galaxy Hubble type). We then have \( \alpha \) perfectly uniformly distributed in the interval \([0, \pi]\) and \( R \) in \([0, 1]\). The redistribution of \( R \) statistically removes finite thickness effects, although each disk has the same thickness within each Hubble type. This uniform redistribution reduces the final spin-spin correlation strength very slightly, indicating that we do not expect systematic effects of global biases to affect our results. However, we would expect the shape-shape correlation of galaxies to result in potential problems (\( R \)-related systematic errors). So, we choose to measure a statistic which does not depend on such correlations.

One practical way to calculate the true correlation signal free of \( R \)-related systematic errors is to use the projected spins; instead of using the given values of \( R \), we set \( R = 0 \) for all galaxies, which amounts to projecting the three-dimensional spin vectors onto the plane of the sky (the plane normal to the line of sight). Using these projected two-dimensional spins, one can construct a real (but two-dimensional) spin correlation function \( \eta_{2D} \) as a function of the three-dimensional galaxy separations as follows. Let us consider two galaxies with unit spins \( \hat{L}_i \) and \( \hat{L}_j \) at \( \hat{x}_i \) and \( \hat{x}_j \), respectively, with a separation \( r = ||\hat{x}_i - \hat{x}_j|| = r = (\hat{r} \cdot \hat{x}_i) \hat{x}_i \). The two-dimensional projected unit spin \( \hat{S} \) for each galaxy can be expressed as \( \hat{S}_i = \hat{S} / ||\hat{S}|| \) and \( \hat{L}_i - \hat{L}_j \) and \( \hat{S}_i \) and \( \hat{S}_j \) are two-dimensional unit separation vectors are \( \hat{y}_i = y_i / y \) and \( \hat{y}_j = y_j / y \). The two-dimensional spin correlation \( \eta_{2D} \) now can be expressed as the difference in angle \( \beta \) between \( \hat{S} \) and \( \hat{y} \). Thus, \( \eta_{2D} = (\cos \beta - \hat{S} \cdot \hat{y}) / \hat{S} \cdot \hat{y} \) with \( \cos \beta = \hat{S} \cdot \hat{y} \). This procedure reduces to \( \hat{S} \cdot \hat{y} \) in the small-angle (flat sky) limit, but is also valid for all-sky data used here. Note that the twofold degeneracy, \( \langle \hat{L}_i \cdot \hat{L}_j \rangle \) is irrelevant for the two-dimensional case where \( \hat{L}_i = 0 \).

To find a three-dimensional spin correlation signal free of the systematic errors involved in \( R \), one can consider the correlation between the three- and two-dimensional unit spin vectors such that \( \eta (r) \approx \langle \hat{L} \cdot \hat{S} \rangle - 1 \), where \( \hat{S} \) and \( \hat{L} \) are calculated from the uniformly redistributed \( \alpha \) and \( R \). Here \( \hat{S} \) is free of the \( R \)-related systematic errors by setting \( R = 0 \), but \( \hat{L} \) still involves \( R \)-related systematic errors. Thus, some fraction of \( \eta (r) \) must be the false signal. As a device from which the false signal is to be filtered out, one can use the following procedure: (1) Generate random 12,122 \( \alpha \)’s. (2) Using these random \( \alpha \)’s, construct two-dimensional random spins \( \hat{S} \). (3) Then calculate the correlation of \( \eta (r) \approx \langle \hat{L} \cdot \hat{S} \rangle \rangle - 1 \). (4) Repeat this process 1000 times with different sets of 12,122 random \( \alpha \)’s and take the average, \( \bar{\eta} (r) \), out of the 1000 sets of the correlations. Then \( \bar{\eta} (r) \) represents purely the false signal only; otherwise \( \bar{\eta} (r) \) would be almost zero. The effective three-dimensional correlation free of the \( R \)-related systematic errors is now obtained as \( \eta (r) = \bar{\eta} (r) - \bar{\eta} (r) \).

One thing that one has to keep in mind for the three-dimensional case, however, is the twofold degeneracy. As explained in § 2, one cannot determine the sign of the radial component of a galaxy spin. Let us assume that we have a galaxy pair whose three-dimensional unit spins and projected two-dimensional unit spins are \( \hat{L} \), \( \hat{S} \), and \( \hat{L}_i \), \( \hat{S}_i \), respectively. Here each three-dimensional unit spin is determined up to twofold ambiguity, say, \( \hat{L}_i \), \( \hat{L}_i \), \( \hat{L}_i \), \( \hat{L}_i \) (\( \hat{L}_i \) and \( \hat{L}_i \) differ by the sign of their radial components). Thus, there are four different ways to correlate the spins of this galaxy pair such that \( \bar{\eta} = \langle \hat{L}_i \hat{L}_j \rangle \), \( \bar{\eta} = \langle \hat{L}_i \hat{L}_j \rangle \), \( \bar{\eta} = \langle \hat{L}_i \hat{L}_j \rangle \), \( \bar{\eta} = \langle \hat{L}_i \hat{L}_j \rangle \). The spin correlation of this galaxy pair given the twofold degeneracy is now taken as the average of the four
combinations: $(f^x_g + f^y_g + f^z_g + f^b_g)/4 - 1/4$. We apply this to every galaxy pair in calculating $\eta(r)$.

Figure 1 plots the resulting $\eta_{3D}$ and $\eta_{E}(r)$ (filled squares) with error bars and compares it with the theoretical predictions (eq. [1]). The error bars are from the numerical formula that we have obtained by the Monte Carlo method. We have generated $N_b$ samples of $10^6$ random spins and calculated the standard deviations of the correlations of the random spins. We have found that the standard deviations are excellently fitted by the following formula: $0.234/ \left( N_b \right)^{1/2}$ for the three-dimensional case and $1/ \left( 8N_b \right)^{1/2}$ for the two-dimensional case. For the Tully galaxies, $N_b$ corresponds to the number of galaxy pairs in each bin.

Note that the observed correlation is measured in redshift space, which causes the observed signal to look flatter than the intrinsic Lagrangian correlation function defined in real space (dashed line). In order to make a better comparison, we convolve the Lagrangian correlation by a one-dimensional Gaussian filter with a peculiar velocity dispersion of $\sigma_v = 150$ km s$^{-1}$ to obtain the theoretical curve in redshift space (solid line). Since we restrict ourselves to spiral galaxies, we use a value of $\sigma_v$ close to the observed dispersion of $126 \pm 10$ km s$^{-1}$ (Davis, Miller, & White 1997) for this class of galaxies. We note that this very cold distribution of field spirals implies that galaxies did not move far from their initial positions, leaving nearest neighbor relations relatively unchanged from their Lagrangian values.

The one-dimensional Gaussian filter instead of a three-dimensional one is used to account for the nonuniform galaxy distribution. Since galaxies are not uniformly distributed, one has to weight $\eta(r)$ by the galaxy-galaxy correlation that is proportional to $r^{-1.8}$ when convolving it. This effectively cancels out the three-dimensional volume factor of $r^2$. For the theoretical curves, a power-law spectrum, $P(k) = k^{-2}$, and the correlation parameter, $a = 0.24$, are used. The spin-spin correlation is of much smaller amplitude of $a^2 \xi(r)^2 \xi(0)^{1/2}$ than $a$ and thus is much harder to measure in simulations. Croft & Metzler (2000) and Heavens et al. (2000) have attempted it and found signals of similar amplitudes. But as a result of their statistics, which are different from ours, it is difficult to compare their findings to ours.

The observed correlation signal is in fairly good accord with the theoretical predictions. The total significance of the observed two-dimensional and three-dimensional correlations at the first three bins are detectable at 95% and 97% confidence levels, respectively, within a distance of a few $h^{-1}$ Mpc, while the correlations diminish to zero at larger separations, as the theory predicts (see § 2). For the total significance, we evaluate the $\chi^2$ from the first three bins (degrees of freedom, $n_\chi = 3$) with the null hypothesis of random spins. Then we calculate the probability of $\chi^2$ exceeding the observed value ($\chi^2_{3D} = 7.78$, $\chi^2_{1D} = 8.95$) and show that the null hypothesis of random spins, i.e., no correlation hypothesis at the first three bins, is rejected at 95% and 97% confidence levels for the two- and three-dimensional cases, respectively. For this $\chi^2$ distribution, the two- and three-dimensional correlations are significant at the 2.0 and 2.4 $\sigma$ levels, respectively.

Another concern that could arise in measuring the spin correlation signal is the overlap effect. When a separation of a pair of galaxies is less than the physical size of the galaxy pair, then the spin correlation signal calculated from that close pair might be affected by the overlap effect. We remeasure the signal excluding those close pairs whose separations are less than twice the sum of the individual radii of the galaxy pair (total 279 galaxy pairs excluded). But it turns out that the excision to twice the radius at which overlap is expected has a negligible effect on the signal (the total significance of the observed signal is slightly lowered from 97% to 94% for the three-dimensional case and from 95% to 94% for the two-dimensional case).

It is also interesting to measure the covariance of $\eta(r)$, $\text{cov} \{ \eta(r), \eta(r) \} \equiv \langle \eta(r)\eta(r) \rangle / \langle \sigma_v \sigma_v \rangle$, between the bins using the 1000 sample sets of random spins. It provides us the degree of independence of the statistics at each bin. We have found $\text{cov} \{ \eta(r), \eta(r) \} \approx O(10^{-3}) \ll 1$ for both the two- and three-dimensional cases, suggesting the statistics at each bin is quite independent of that of the neighboring bins.

4. DISCUSSIONS AND CONCLUSIONS

There are other sources of shear that could change the apparent direction of the spin axis. Above all, shears from weak lensing can be a good example. But the shear effect on the galaxy spin axis from the weak lensing is much smaller in this low-redshift sample; to estimate the magnitude of the weak-lensing shear, one has to consider the spatial correlation of the convergence $\kappa$, defined as the ratio of the observed galaxy surface density to the critical surface density (the surface density that can just refocus the light beam in the case of null shear). But the expected weak-lensing shear is less than 1% at $z < 1$ for sources at redshift $z \sim 1$ and grows as $\kappa \propto z^{0.8}$ (Jain & Seljak 1997), so the expected weak-lensing shear effect on the galaxy spin axis for our sample, $z \approx 0.02$ is $O(10^{-4})$ at a separation of $1 h^{-1}$ Mpc, 1 order of magnitude smaller than that of the local cosmic shear we measure.

Given that the dominant shear effect on the galaxy alignments at low redshift is from the local cosmic shear, the detection of galaxy alignments could affect recent observational surveys for the weak-lensing effect on the distortion of the galaxy shapes (van Waerbeke et al. 2000) and the interpretation of the lensing effect (Catelan et al. 2000; Heavens et al. 2000).
It is beyond the scope of this Letter to derive a detailed quantititative calculation of the impact of the observed shape-shape correlation on weak-lensing surveys, which is being addressed in a separate paper (Crittenden et al. 2000). Here we will make a brief qualitative estimate that shows that the intrinsic alignments may introduce a nonnegligible bias.

To estimate the impact on weak lensing, we project the three-dimensional spin-spin correlation (eq. [1]) using the small-angle approximation onto the sky to obtain a projected two-dimensional angle-angle correlation weighted by the galaxy-galaxy correlation function \( \xi(r) \sim (r/r_0)^{-1.5} \) with \( r_0 = 5.5 \, h^{-1} \, \text{Mpc} \):

\[
\eta_\gamma(y) = \frac{\int_{-\infty}^{\infty} \eta_{2D}(y^2 + z^2) [1 + \xi(y^2 + z^2)] dz}{\int_{-\infty}^{\infty} [1 + \xi(y^2 + z^2)] dz}; \quad (2)
\]

\( L \) is the depth of the galaxy distribution in the source plane. The dilution effect causes \( \eta_\gamma \propto 1/L \), and the usual approximation is to make \( L \to \infty \), stating that two galaxies that appear close in projection are not actually close in real space. The fact that galaxies cluster to each other modifies this assumption such that galaxies that are close in projection actually have an intrinsic probability of being neighbors that is enhanced by the correlation function. To estimate the effect, we use \( L = 1 \, \text{Gpc} \) (comoving) and model \( \eta_{2D} = 0.01/r \) for \( r > 1 \, \text{Mpc} \) and \( \eta_{2D} = 0.01 \) at smaller separations. Placing the source at a typical comoving angular diameter distance of 2800 \( h^{-1} \, \text{Mpc} \) (corresponding to \( z \sim 1 \) in an \( \Omega_m = 0.65, h = 0.7 \) universe; see Pen 1999) and assuming nonevolving comoving correlation functions, we find an apparent correlation at \( 1^\circ \) of \( \eta_\gamma(1^\circ) \sim 0.00024 \), dropping as \( 1/\gamma \) at larger scales.

Weak-lensing surveys measure the correlation function of the shear \( \gamma_\gamma \) at separation \( r \), where \( \gamma_\gamma \), \( i = 1, 2 \) are the two components of the symmetric traceless shear tensor. Since equation (2) correlates galaxies assuming unit ellipticities, it gives a typical intrinsic correlation-induced shear amplitude

\[
c(r) = \langle \gamma_{\gamma i}(0) \gamma_{\gamma j}(r) + \gamma_{\gamma j}(0) \gamma_{\gamma i}(r) \rangle = \langle \epsilon \epsilon \cos 2\Delta\theta \rangle = 2\langle \epsilon \rangle^2 \left( \cos^2 \Delta\theta - \frac{1}{2} \right) = 2\langle \epsilon \rangle^2 \eta_{2D}(r) \sim 2 \times 10^{-4},
\]

where we used \( \langle \epsilon^2 \rangle^{1/2} = 0.6 \) as given by Kaiser (1998). We note a recent detection on a 1' scale (van Waerbeke et al. 2000) of a candidate weak-lensing signal for a top-hat convolved shear variance, which gives \( c(1') \sim 5 \times 10^{-4} \) when translated into our correlation function. This is somewhat larger but still of comparable magnitude and angular dependence as our intrinsic alignment estimate. This model has made many simplifying assumptions, the most crucial one of which is that the shape-shape and galaxy-galaxy correlation functions do not evolve and that the depth distribution of source galaxies is 1 Gpc, all of which may be uncertain by at least a factor of 2. A direct measurement of each of these quantities is essential to fully quantify the impact of shape-shape alignment on weak lensing.

We note, however, that one test can be made that would probe for the presence of intrinsic correlations. The observed shear field \( \gamma_\gamma \) can be decomposed into an “electric” (\( E \)), or potential, flow component and a “magnetic” (\( B \), or curl, component (Pen 2000). Weak lensing predicts \( B = 0 \), while this is not in general the case for shape-shape alignment, which predicts a comparable strength of the \( E \) and \( B \) signals. A measurement of \( B \) would thus provide a general control experiment.

We have estimated the expected strength of the spin correlation normalized to numerical simulation results (LP00a) in the frame of the first-order linear perturbation theory. Then we have measured the spin correlation signal directly from the observed spiral galaxies from the Tully catalog and tested our theoretical predictions against the observed signal. Both the predicted and observed amplitudes are of order of 1% at a separation of 1 \( h^{-1} \, \text{Mpc} \), in agreement with each other. Given our results, we conclude that past surveys would not have had enough sensitivity to detect this signal.

Qualitative estimates show that these correlations may have a nonnegligible effect on statistical weak-lensing surveys. We have proposed using the “magnetic,” or curl, component of the apparent shape-shape alignment to discriminate between intrinsic shear and lensing-induced shear.

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