THE INTRINSIC INCLINATION OF GALAXIES EMBEDDED IN COSMIC SHEETS AND ITS COSMOLOGICAL IMPLICATIONS: AN ANALYTIC CALCULATION

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ABSTRACT

We investigate analytically a large-scale coherence in the orientation of galaxies embedded in two-dimensional sheetlike structures in the framework of tidal torque theory. Assuming that the galaxy spin and the surrounding matter fields are intrinsically aligned in accordance with the tidal torque model, we first derive analytically the probability distribution of the galaxy position angles and evaluate the degree of their inclinations relative to the plane of the sheet. Then, we apply our analytic approach to the nearby spiral galaxies in the Local Supercluster and provide theoretical explanations about why and to what degree the nearby spiral galaxies are inclined relative to the supergalactic plane. Finally, we conclude that the observed large-scale coherence in the orientation of nearby spiral galaxies relative to the supergalactic plane can be quantitatively understood in terms of the intrinsic galaxy alignment predicted by the tidal torque theory and that the spins of luminous galaxies might be more strongly aligned with the surrounding matter than with the underlying dark halos. If applied to large-scale surveys like the Sloan Digital Sky Survey, our analytic approach will allow us to measure accurately the strength of the intrinsic galaxy alignment, which plays the role of statistical error in weak lensing searches and can be used as a fossil record to reconstruct cosmology.

Subject headings: cosmology: theory — large-scale structure of universe

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1. INTRODUCTION

A flurry of recent cosmological research has been focused on studying intrinsic galaxy alignment. The question of intrinsic galaxy alignment is closely related to the origin of the galaxy angular momentum. The standard model for the origin of the galaxy angular momentum is the tidal torque theory (Peebles 1969; Doroshkevich 1970; White 1984). According to this theory, galaxy angular momentum is generated by the early tidal interaction of the galaxy with the surrounding matter that continued until the moment of turnaround.

A generic prediction of the tidal torque theory is the existence of a local correlation between the spin and the matter fields: the spin axes of protogalaxies are preferentially aligned with the intermediate principal axes of the tidal shears from the surrounding matter. The degree of this intrinsic galaxy alignment must be highest at the moment of turnaround. In the subsequent evolution, the galaxies are likely to gradually lose the initial memory about the surrounding matter as a result of the complicated nonlinear effects, with their intrinsic alignments diminishing in strength as a consequence.

An important question in cosmology is whether the intrinsic alignment remains at present epoch to a statistically significant degree or not. It is important in cosmology since the intrinsic galaxy alignment plays the role of systematic error in weak gravitational lensing searches (Heavens et al. 2000; Croft & Metzler 2000; Catelan et al. 2001; Crittenden et al. 2002; Hirata et al. 2004). Besides, it can provide a crucial clue to the unsolved problem of galaxy formation (Dubinski 1992; Catelan & Theuns 1996; Porciani et al. 2002a, 2002b; Navarro et al. 2004) and can also be used as a fossil record to reconstruct the cosmology (Lee & Pen 2000, 2001, 2002).

Without knowing the tidal shear field accurately, it is difficult to measure, in practice, the strength of the intrinsic alignment directly from observational data. One possible way is to measure it indirectly from $N$-body simulation data (Lee & Pen 2000; Heavens et al. 2000; Porciani et al. 2002a, 2002b). However, using $N$-body data, what one can measure is only the intrinsic alignment of underlying dark halos rather than that of the observable luminous parts of galaxies. Although the standard theory of galaxy formation assumes that the spin axes of luminous parts align with those of dark halos (Mo et al. 1998), it was hinted by recent gasdynamical simulations (Chen et al. 2003; Navarro et al. 2004) that the luminous parts could conserve the initial memory of the intrinsic shear-spin correlation better than the dark matter parts, which prevents us from taking the simulation results as real ones. Lee & Pen (2002) attempted to measure the strength of the intrinsic alignment directly from observational data by reconstructing the tidal shear field with the data from the Point Source Catalog Redshift Survey. Although they claimed a detection of an intrinsic shear-spin correlation, their measurement was far from being accurate because of the high statistical noise.

The difficulty in measuring the intrinsic galaxy alignment lies in the fact that it is a local correlation between the galaxy spin and the surrounding matter fields effective only over a few megaparsecs in three-dimensional space. However, it is often observed in the universe that the galaxies are surrounded by a coherent two-dimensional sheetlike structure that usually extends over tens of megaparsecs. For such galaxies that are embedded in a sheet, one may expect a large-scale coherent orientation (Navarro et al. 2004). It does not mean that the existence of cosmic sheets leads logically to the expectation of a large-scale coherence in the orientation of the galaxies. The two concepts are separate: the intrinsic galaxy alignment is due to the tidal torques from the surrounding matter, while sheets initially form through gravitational clustering as collapsed objects (Shandarin et al. 1995). Sheets are just one example of the large-scale structures that surround and tidally interact with galaxies. The expectation of a coherence in the orientation of the galaxies embedded in a sheet comes not from the existence...
of the sheet itself but from the large-scale coherent pattern in the two-dimensional distribution of matter in the surrounding sheet. Therefore, it may be possible to predict the coherent orientation of the galaxy spin axes relative to the plane of the sheet in the framework of tidal torque theory. Furthermore, it may be also possible to evaluate quantitatively the strength of this intrinsic inclination of galaxies by an analytic method. The goal of this Letter is to explore these possibilities.

2. ANALYTIC EVALUATIONS

2.1. Key Assumptions

To evaluate the intrinsic alignment of galaxies embedded in sheets, we assume the following:

1. The galaxy angular momentum or the galaxy spin vector \( \mathbf{L} \) originates from the tidal shear effect from the surrounding matter at the protogalactic stage, which continued until the moment of turnaround. The growth of the protogalaxy angular momentum is determined by its inertia tensor (\( \mathbf{I} \)) and by the moment of turnaround. The principal axes of the inertia tensor (or, similarly, the intermediate principal axis of the tidal shear tensor) results in a preferential alignment of the protogalaxy spin axis with the intermediate principal axis of the tidal shear tensor.

2. The strength of the intrinsic galaxy alignment with local shears at the present epoch can be expressed as the following simple quadratic relation (Lee & Pen 2002):

\[
\langle L, L' \rangle = \frac{1 + c}{3} \delta_{L} - c \hat{T}_{ij} \hat{T}_{ij},
\]

where \( \hat{T} \) is the rescaled traceless shear tensor defined as \( \hat{T}_{ij} = T_{ij}/|T| \), with \( T_{ij} = \text{Tr} (\mathbf{T}) \delta_{ij}/3 \), and \( c \) is a correlation parameter (see Appendix A in Lee & Pen 2002) introduced to quantify the strength of the intrinsic shear-spin alignment in the range of \([0, 1]\). The value of \( c \) cannot be determined from first physical principles since it includes all the nonlinear effects after the moment of turnaround. One should determine its value empirically.

3. The probability distribution of galaxy spin vectors, \( P(\mathbf{L}) \), is well approximated as a Gaussian distribution (Catelan & Theuns 1996).

4. A cosmic sheet is the first collapsed object (Shandarin et al. 1995), forming as early as the moment of turnaround (Pauls & Melott 1995). The minor axis of \( \mathbf{T} \) at each point on a sheet (i.e., the direction of its maximum compression) is almost perpendicular to the plane of the sheet. We coherently approximate the lowest eigenvalue of each \( \mathbf{T} \) on a sheet as zero.

Following the fourth hypothesis, we approximate \( \lambda_i \)'s identically as zero at all points on the sheet. Therefore, in the frame of the principal axis of the tidal shear tensor at each point, the polar angle \( \theta \) of a galaxy spin vector \( \mathbf{L} = (L \sin \theta \cos \phi, L \sin \theta \sin \phi, L \cos \theta) \) represents the angle of the spin axis relative to the plane of the sheet (i.e., the galaxy position angle).

To derive the distribution of the galaxy position angles relative to the plane of the sheet, we integrate equation (2) in the principal axis frame of the tidal shear as \( P(\theta) = \int_{0}^{2\pi} P(\mathbf{L}, \theta, \phi) L^2 d\phi \) and derive the following analytic expression:

\[
P(\theta) = \frac{1}{2\pi} \prod_{i=1}^{3} (1 + c - 3c \hat{\lambda}_i) \exp \left( \frac{\hat{\lambda}_i}{\sigma} \right) \cdot \int_{0}^{2\pi} \sin^2 \theta \cos^2 \phi + \sin^2 \theta \sin^2 \phi + \cos^2 \theta \exp \left( -\frac{\hat{\lambda}_i}{\sigma} \right) d\phi,
\]

where \( \hat{\lambda}_i \) is assumed to be in the range of \([0, \pi/2]\). Here the three \( \hat{\lambda}_i \)'s (\( i = 1, 2, 3 \)) are the rescaled eigenvalues of \( \mathbf{T} \) constrained by \( \Sigma, \hat{\lambda}_i = 1 \). For the case of \( \hat{\lambda}_i = 0 \), they can be expressed in terms of the two eigenvalues \( \lambda_1 \) and \( \lambda_2 \) as

\[
\hat{\lambda}_1 = \frac{2\lambda_1 - \lambda_2}{\sqrt{6(\lambda_1 - \lambda_2)^2}},
\]

\[
\hat{\lambda}_2 = \frac{2\lambda_2 - \lambda_1}{\sqrt{6(\lambda_1 - \lambda_2)^2}},
\]

\[
\hat{\lambda}_3 = \frac{-\lambda_1 + \lambda_2}{\sqrt{6(\lambda_1 - \lambda_2)^2}}.
\]

Equations (3)–(4) show how the probability distribution of the galaxy position angles, \( P(\theta) \), depends on the eigenvalues of \( \lambda_1 \) and \( \lambda_2 \) as well as on the correlation parameter \( c \).

The conditional distributions of the two eigenvalues provided that \( \lambda_3 = 0 \) can be derived by using Bayes’s theorem: \( p(\lambda_i | \lambda_j = 0) = [p(\lambda_i, \lambda_j = 0)/p(\lambda_j = 0)](i = 1, 2) \). Here the two-point joint distribution \( p(\lambda_i, \lambda_j) \) and the one-point distribution \( p(\lambda_i) \) are all obtained analytically by Lee & Shandarin (1998). Using these results, we derive

\[
p(\lambda_1 | \lambda_3 = 0) = \frac{27(3\lambda_1^2 + \sqrt{2})}{16\pi\sigma} \exp \left( -\frac{3\lambda_1^2}{\sigma^2} \right)
\]

\[
+ \frac{\lambda_1^2}{\sigma^2} \exp \left( -\frac{9\lambda_1^2}{2\sigma^2} \right)
\]

\[
+ \frac{\sqrt{3}\pi\lambda_1}{12\sigma} \left( \frac{9\lambda_1^2}{\sigma^2} - 8 \right) \exp \left( -\frac{45\lambda_1^2}{16\sigma^2} \right)
\]

\[
\times \left[ \text{erf} \left( \frac{\sqrt{3}\lambda_1}{4\sigma} \right) + \text{erf} \left( \frac{\sqrt{3}\lambda_1}{4\sigma} \right) \right].
\]
Fig. 1.—Conditional probability density distributions of the largest and the
second largest eigenvalues of an intrinsic shear tensor provided that its smallest
eigenvalue has the value of zero. The dotted lines locate the most probable
eigenvalue for each case.

\[
p(\lambda_2|\lambda_1 = 0) = \frac{27(3 + \sqrt{3})}{16\pi\sigma^9} \left[ \frac{\lambda_2^2}{\sigma^2} \exp\left( -\frac{9\lambda_2^2}{2\sigma^2} \right) \right] \\
+ \frac{3\sqrt{3}\pi\lambda_2}{12\sigma} \left( 8 - \frac{9\lambda_2^2}{\sigma^2} \right) \exp\left( -\frac{45\lambda_2^2}{16\sigma^2} \right) \\
\times \text{erfc} \left( \frac{3\sqrt{3}\lambda_2}{4\sigma} \right).
\]

where \( \sigma \) is the rms fluctuation of the linear density field.

Figure 1 plots the above conditional distributions (eqs. [5] and [6]). The dotted lines locate the most probable values of the two eigenvalues provided that \( \lambda_1 = 0: \lambda_1^{\max} \approx 0.8 \sigma; \lambda_2^{\max} \approx 0.3 \sigma. \) We also determined the conditional mean and the standard deviation of each eigenvalue from equations (5) and (6): \( \lambda_1 = 0.86 \sigma, \sigma_{\lambda_1} = 0.28 \sigma; \lambda_2 = 0.38 \sigma, \sigma_{\lambda_2} = 0.21 \sigma. \)

Putting \( \lambda_1^{\max} \) and \( \lambda_2^{\max} \) into equation (3), we can investigate how the distribution of the galaxy position angles relative to the plane of the sheets varies with the value of the correlation parameter \( c. \) Figure 2 plots \( P(\theta) \) for five different cases of \( c = 1, 0.7, 0.5, 0.3 \) and 0 (solid, dashed, long-dashed, dot-dashed, and dotted lines, respectively). As expected, for the case of \( c = 0, P(\theta) \) is uniform, and the larger the value of \( c \) is, the more sharply \( P(\theta) \) increases in the small-angle section. In other words, the stronger the intrinsic shear-spin correlation, the more inclined the galaxy spins relative to the sheet. Equation (3) also allows us to evaluate the average position angles: \( \bar{\theta} = \int_0^{\pi/2} \theta P(\theta) d\theta. \) We find \( \bar{\theta} = 29^\circ, \) if \( c = 0.9 \) (see in § 3).

3. THEORY VERSUS OBSERVATION

A vivid example of galaxies that are embedded in a two-
dimensional sheet comes from the neighborhood of our Milky
Way, where nearby spiral galaxies are assembled in the Local
Supercluster (de Vaucouleurs et al. 1991). Although there were
some reports of detecting a large-scale coherent orientation of the
observed nearby spiral galaxies relative to the Local Supercluster (e.g., Gregory et al. 1981; Helou & Salpeter 1982; Flin & Godlowski 1986; Garrido et al. 1993), these previous
reports often suffer from small sample sizes, thus hardly being
compelling evidence.

However, very recently, Navarro et al. (2004) used a relatively
large sample of nearby galaxies from the Principal Galaxy
Catalog (PGC; Paturel et al. 1997) and estimated the number
distribution of nearby disk galaxies as a function of the
supergalactic position angles. They found that the spin axes of
nearby edge-on spiral galaxies \( (cz < 1200 \text{ km s}^{-1}) \) are strongly
inclined relative to the supergalactic plane and concluded that the
observed result is consistent qualitatively with tidal torque theory. Yet, they did not make any quantitative comparison of the observed result with the predictions of tidal torque theory.

To make a quantitative comparison, we evaluate the number
distribution of galaxies embedded in sheets using equation (3). Figure 3 plots the results. The dot-dashed line represents our
theoretical prediction with the choice of \( c = 0.9 \) (the best-fit value), while the histogram corresponds to the observational result from the PGC (see Fig. 2 in Navarro et al. 2004). Obvi-
ously, the theoretical curve agrees with the histogram very well. Navarro et al. (2004) determined the average value of the
position angles from the observed edge-on disk galaxies to be \( \bar{\theta}_{\max} \approx 25^\circ, \) which is in agreement of the theoretical value that we obtained assuming \( c = 0.9 \) in § 2.

It is worth noting that the best-fit value of \( c = 0.9 \) is 3 times
higher than that found in an \( N \)-body simulation (Lee & Pen
2000, 2002). It may imply that the luminous parts of galaxies tend to keep the initial memory of the surrounding matter field
better than their dark matter counterparts, consistent with the
results from recent gasdynamical simulations (Chen et al. 2003;
Navarro et al. 2004).
4. CONCLUSION

We have predicted analytically a large-scale coherence in the orientation of galaxies embedded in sheets using tidal torque theory. Our analytic model reproduces the observed inclinations of nearby spiral galaxies in the Local Supercluster remarkably well, providing a physical quantitative understanding of the observables. It should be emphasized here, however, that the prediction of the coherent orientation of galaxies embedded in a sheet should not be taken as identical to the existence of the sheet itself. The coherent orientation of the galaxies is caused by the tidal torquing from the surrounding matter, which is different from the formation of cosmic sheets in the universe.

By comparing our analytic prediction with the observational result, we also measured quantitatively the strength of the intrinsic galaxy alignment and found that the luminous galaxies seem to conserve their angular momentum better than the underlying dark halos after the moment of turnaround. Our final conclusion is this: our analytic calculation, if applied to observational data from large-scale surveys like the Sloan Digital Sky Survey, will allow us to measure accurately the strength of the intrinsic galaxy alignment, and this will have an impact on weak gravitational searches and can also be used as a fossil record to reconstruct the cosmology.

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