The Alignments of Disk Galaxies with the Local Pancakes

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ABSTRACT

We analyze the Tully catalog of nearby galaxies to investigate the local pancaking effect on the orientation of disk galaxies. We first select only those edge-on disk galaxies in the catalog whose axis-ratios are less than 0.1 to measure their spin axes unambiguously. A local pancake at the location of each selected galaxy is found as a plane encompassing the two nearest neighbor disks. Then, we examine statistically the inclinations of the galaxy spin axes relative to the local pancake planes. It is detected that the Tully disk galaxies tend to be inclined onto the local pancake planes, and the average inclination angles decrease with the pancake scale. We also construct a theoretical model for the inclination of disk galaxies relative to the local pancakes in the frame of the linear tidal torque theory. The comparison of the theoretical prediction with the observational result demonstrates a good agreement. Finally, we conclude that it is a first detection of the local pancaking effect on the orientation of disk galaxies, which is consistent with the scenario that the gravitational tidal field promotes the formation of pancakes on small mass scale.

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

1. INTRODUCTION

The standard theory of structure formation based on the cold dark matter (CDM) paradigm explains that the building blocks of cosmic structures in the universe are virialized halos made up of cold dark matter particles, and that these CDM halos form hierarchically via gravity from the primordial density fluctuations with a characteristic spectrum.

Although this standard theory has been remarkably successful in explaining the observed properties of the universe on the galaxy cluster scale, its validity on the galactic scale is still inconclusive, since observational data seemed inconsistent with the theory on that scale (e.g., Kauffmann et al. 1993; Klypin et al. 1999; Moore et al. 1999; Binney & Evans 2001).
Confronted with observational challenges, various theoretical attempts have been recently made to refine the standard theory of structure formation on the galactic scale. One of such attempts is the currently proposed “broken hierarchy” scenario (e.g., Bower et al. 2005, and references therein). According to this idea, the gravitational clustering to form dark halos does not proceed in a perfectly hierarchical way on all scales, unlike the prediction of the standard theory. Rather, the scenario suggests that the clustering process take on a somewhat anti-hierarchy on small mass scales as the gravitational tidal field favors the formation of a pancake (an object collapsed along one direction) over that of a halo (an object collapsed along all three directions). This scenario has been shown to be capable of resolving several conflicts with observational data. For example, Mo et al. (2005) recently showed that if the pre-virialization induced by the pancaking effect is taken into account, the observed HI mass function and the faint-end slope of the galaxy luminosity function can be explained within the context of the standard structure formation theory.

Promising as this scenario seems, it is not an easy task to test it against observations and to detect directly the local pancaking effect. A possible way to detect the pancaking effect is to investigate the anisotropy in the orientation of galaxies induced by the gravitational tidal field. According to the tidal torque theory, the angular momentum of a galaxy is originated by the tidal interaction with the surrounding matter. A generic prediction of the tidal torque theory is that the direction of the galaxy angular momentum is not random but aligned with a local tidal shear tensor (e.g., Dubinski 1992; Lee & Pen 2000). Thus, if a galactic halo is embedded in a local pancake that formed earlier than the galactic dark halo, then a correlation between the galaxy spin axis and the pancake principal axis should exist.

In fact, it was claimed by many observational reports that the galaxy spin axes are correlated with the surrounding matter distribution (Helou & Salpeter 1982; Flin & Godlowski 1986; Kashikawa & Okamura 1992; Garrido et al. 1993). Very recently, more convincing evidences for the anisotropy in the orientations of the galaxy spin axes induced by the tidal fields of the surrounding matter have been found. Navarro et al. (2004) detected that the spin axes of the nearby edge-on spirals in the Principal Galaxy Catalog (PGC, Paturel et al. 1997) have a strong tendency to lie parallel to the Super-galactic plane (SGP). Trujillo et al. (2005) also found that the spin axes of the galaxies located near the shells of the largest cosmic voids lie preferentially on the void surface.

Note, however, that these observations found evidences only for those particular cases that the galaxies are surrounded by the large-scale structure with a flat surface. In other words, what was detected so far is not the effect of the local pancake but the effect of the large scale coherence of the surrounding matter on the orientations of the galaxy spin axes. Here, our goal is to detect a local pancaking effect by investigating the anisotropy on the
orientation of the galaxy spins from observational data. In §2, we determine the probability density distribution of the inclination angles of the Tully disk galaxies relative to the local pancake planes. In §3, we model analytically the anisotropy in the orientation of the galaxy spin axes in the frame of the tidal torque theory, and compare the analytic prediction with observational data. The results are discussed and a final conclusion is drawn in §4.

2. OBSERVATIONAL ANALYSIS

To detect the intrinsic alignment of the galaxies and local pancake in the real universe, we use the Tully catalog. In the Tully catalog, 35674 nearby galaxy properties observed from the whole sky are piled up. Among them we make a subsample of 12122 disk galaxies which have a type 0−9 listed in Third Reference Catalog of Bright Galaxies (RC3, de Vaucouleurs et al. 1991). The median redshift of the subsample is 5180 km/s. Note that the gravitational weak lensing effect can be neglected at this low redshift (Mandelbaum et al. 2005).

We focus our analysis on this subsample of spirals for the following reason. The spiral galaxies have relatively low velocity dispersion, approximately 126 ± 10 km/s (Davis et al. 1997). It indicates that the spiral galaxies did not move far from their initial Lagrangian positions in the subsequent evolution. Thus, the positions of the spirals may be optimal to define the local pancake planes.

First, we measure the spin direction of the spiral galaxies by using the position angle (PA) on the sky and the projected axial ratio (e). Assuming that the geometry of the sky is flat, the spin vector of each galaxy in the spherical coordinate system is obtained from \( \tan(\text{PA}) = \hat{L}_\theta / \hat{L}_\phi \) and \( e = |\hat{L}_r| \). For the calculation of the spin vectors, two fold degeneracy should be accounted for. In other words, it is hard to decide whether the galaxy rotates clockwise (\( \hat{L}_r \)) or anticlockwise (\( -\hat{L}_r \)). We consider the degeneracy problem statistically as follow. The probability distribution \( p(\cos \theta) \) is calculated by \( \frac{p(\cos \theta_1) + p(\cos \theta_2)}{2} \), where \( \theta_1 \) and \( \theta_2 \) are the angles of the unit vector normal to the local pancake with \( \hat{L}_r \) and \( -\hat{L}_r \), respectively. To reduce the degeneracy, we use only edge-on galaxies whose axial ratio is less than 0.1. The total number of the edge-on galaxies is found to be 116. The spin directions calculated in the spherical coordinates are transformed to those in the Cartesian coordinates with the given equatorial coordinate positions (1950 equinox for RA and DEC).

Now, a local pancake has to be determined at each given edge-on spiral whose spin vector is obtained. As mentioned in §1, theoretically the local pancake is defined as a sheet-like structure gravitationally collapsed along the major principal axis of a local shear. In practice, however, it is hard to apply this theoretical method for the observational data. Instead, we
employ the following practical scheme. At the location of each edge-on spiral, we first find the two nearest neighbors among all 12122 spirals in the subsample, and determine a local pancake as the plane encompassing the galaxy itself and its two nearest neighbors. Figure 1 illustrates the configuration of an edge-on galaxy and its local pancake. The logic for this scheme is as follows: If the formation of a small-mass galactic halo is really preceded by that of a larger-mass local pancake at the early epoch, then the two-dimensional coherence in the locations of the neighbor galaxies should be expected. In other words, the placements of the nearest neighbors should be more or less arranged in the plane of the local pancake where they are all embedded. The scale of a local pancake at a given edge-on spiral is determined by the distance from the galaxy to the second nearest neighbor. It is worth mentioning again that we consider only the spiral galaxies since their peculiar velocities are relatively small so that they are expected to conserve their initial Lagrangian position.

Now that a local pancake at the location of each edge-on disk is defined, we compute the cosines of the angles between the spin axis and the unit vector normal to the pancake plane (see Fig. 1) as $\cos \theta = |\hat{L} \cdot (\hat{R}_1 \times \hat{R}_2)|$, where $\theta \in [0, \pi/2]$, $\hat{L}$ is the unit spin vector of an edge-on galaxy, and $\hat{R}_1, \hat{R}_2$ are the unit vectors of the displacement to the first and the second nearest neighbors, respectively. The unit vector normal to the local pancake is determined as $\hat{R}_1 \times \hat{R}_2$. From this, we compute the probability density distribution, $p(\cos \theta)$, and the average, $|\cos \alpha|$, which are shown as histograms with the error bars in the upper and the lower panels of Figure 2, respectively. The errors for estimating $p(\cos \theta)$ are just Poissonian. For the errors involved in measuring $\langle |\cos \theta| \rangle$, we use the statistical deviation, $\sqrt{\left(\frac{1}{3} - \frac{1}{2}\right)/N}$, ($N$: the number of galaxies in each bin) from the no-inclination case of $\langle |\cos \theta| \rangle = 1/2$ and $\langle |\cos^2 \theta| \rangle = 1/3$.

The observational results shown in Figure 2 reveal that the spin axes of the disk galaxies tend to be inclined onto the plane of the local pancakes, and that the degree of the inclination decreases with the pancake scale. It reflects that the galaxy inclination to the pancake plane is indeed a local correlation with the gravitational tidal field. Suffering from the large error-bars due to the small sample size, we test the rejection of the no-inclination hypothesis, using the observed data points. It is found that the no-inclination hypothesis is rejected at the 89% confidence level.

### 3. THEORETICAL ANALYSIS

To construct a theoretical model for the inclinations of disk galaxies relative to the local pancakes, we assume the following.
1. The angular momentum of a disk galaxy is originated by the initial tidal interaction with the surrounding matter (Doroshkevich 1970; White 1984), which induces a correlation in the orientation of the galaxy angular momentum vector, \( \mathbf{L} = (L_i) \), with the local tidal shear tensor, \( \mathbf{T} = (T_{ij}) \) defined as the second derivative of the perturbation potential.

2. On small-mass halo scales, the gravitational tidal field promotes the formation of a pancake (Zel’dovich 1970; Mo et al. 2005) that precedes the formation of a low-mass halo. The formation of a local pancake is well described by the Zel’dovich approximation (Zel’dovich 1970), according to which the local density at present epoch is given as:

\[
\rho = \frac{\bar{\rho}}{(1 - \lambda_1)(1 - \lambda_2)(1 - \lambda_3)},
\]

where \( \bar{\rho} \) is the mean density of the Universe, \( \lambda_1, \lambda_2, \lambda_3 \) are the three eigenvalues of the local tidal shear tensor, \( \mathbf{T} \) in a decreasing order. Equation (1) implies that the formation of a local pancake (i.e., a first shell crossing) occurs at present epoch if the largest eigenvalue, \( \lambda_1 \), reaches unity.

3. The minor principal axis of the inertia momentum tensor of a local pancake is aligned with the major principal axis of the local shear tensor, since the gravitational collapse along the major principal axis of the local shear tensor forms a pancake.

4. Let \( \mathbf{L} = (L \sin \theta \cos \phi, L \sin \theta \sin \phi, L \cos \theta) \) be a galaxy angular momentum vector in the principal axis system of the inertia momentum tensor of a local pancake. Now that Lee et al. (2005) already found an analytic expression for the probability density distribution of the cosines of the angles between \( \mathbf{L} \) and the major principal axis of the inertia momentum tensor (which is the minor principal axis of \( \mathbf{T} \) according the above third assumption), one can derive straightforwardly the probability density distribution of the cosines of the angles between \( \mathbf{L} \) and the minor principal axes of the inertia momentum tensors (which is the major principal axes of \( \mathbf{T} \)) by rotating the minor to the major principal axis as

\[
p(\cos \theta) = \frac{1}{2\pi} \prod_{i=1}^{3} (1 + c - 3\hat{\lambda}_i^2)^{-\frac{1}{2}} \int_0^{2\pi} \left( \frac{\sin^2 \theta \cos^2 \phi}{1 + c - 3\hat{\lambda}_2} + \frac{\sin^2 \theta \sin^2 \phi}{1 + c - 3\hat{\lambda}_3} + \frac{\cos^2 \theta}{1 + c - 3\hat{\lambda}_1^2} \right)^{-\frac{3}{2}} d\phi,
\]

where, \( c \) is a correlation parameter in the range of \([0, 1]\). Here, \( \{\hat{\lambda}_1, \hat{\lambda}_2, \hat{\lambda}_3\} \) represent the three eigenvalues (in a decreasing order) of the unit traceless tidal shear tensor, \( \hat{\mathbf{T}} = (\hat{T}_{ij}) \) defined as \( \hat{T}_{ij} \equiv \hat{T}_{ij} / |\hat{T}| \) with \( \hat{T}_{ij} \equiv T_{ij} - \text{Tr}(\mathbf{T})\delta_{ij}/3 \), related to \( \{\lambda_1, \lambda_2, \lambda_3\} \),
as

\[ \hat{\lambda}_1 = \frac{2\lambda_1 - \lambda_2 - \lambda_3}{\sqrt{6(\lambda_1^2 + \lambda_2^2 + \lambda_3^2 - \lambda_1\lambda_2 - \lambda_2\lambda_3 - \lambda_1\lambda_3)}}, \]  
(3)

\[ \hat{\lambda}_2 = \frac{-\lambda_1 + 2\lambda_2 - \lambda_3}{\sqrt{6(\lambda_1^2 + \lambda_2^2 + \lambda_3^2 - \lambda_1\lambda_2 - \lambda_2\lambda_3 - \lambda_1\lambda_3)}}, \]  
(4)

\[ \hat{\lambda}_3 = \frac{-\lambda_1 - \lambda_2 + 2\lambda_3}{\sqrt{6(\lambda_1^2 + \lambda_2^2 + \lambda_3^2 - \lambda_1\lambda_2 - \lambda_2\lambda_3 - \lambda_1\lambda_3)}}. \]  
(5)

Basically, equation (2) is obtained from the formula given in Lee et al. (2005) simply by exchanging \( \hat{\lambda}_1 \) with \( \hat{\lambda}_3 \).

5. The correlation parameter, \( c \), in equation (2) depends on the filtering scales on which the galaxy angular momentum \( \mathbf{L} \) and the local shear tensor \( \mathbf{T} \) are smoothed. The correlation parameter \( c \) is a constant only if the two scales are the same. If they are different, then the correlation parameter is no longer a constant but varies with the filter scales (Lee & Pen 2001) as

\[ c = c_0 \frac{\sigma(R_2)}{\sigma(R_G)}, \]  
(6)

where \( c_0 \) is a constant, and \( \sigma(R_2) \) is a rms fluctuation of the linear density field smoothed on the pancake scale \( R_2 \). Here, \( R_G \) represents the galactic scale \( \approx 0.55 h^{-1} \text{Mpc} \) (Bardeen et al. 1986) on which the angular momentum vector \( \mathbf{L} \) is smoothed.

To complete equation (2), one has to specify the values of \( \{\hat{\lambda}_i\}_{i=1}^3 \) and \( c \). According to the second assumption, a local pancake of the scale length \( R_2 \) forms when the largest eigenvalue of \( \lambda_1 \) of the tidal shear tensor smoothed on the scale \( R_2 \) reaches unity. As for the other two eigenvalues, \( \lambda_2 \) and \( \lambda_3 \), one may use the most probable values under the constraint of \( \lambda_1 = 1 \).

Using the probability density distributions, \( p(\lambda_1, \lambda_2, \lambda_3) \) and \( p(\lambda_1) \), derived by Doroshkevich (1970), and with the help of the Bayes theorem, we evaluate the constrained joint probability density distribution of \( \lambda_2 \) and \( \lambda_3 \) as

\[ p(\lambda_2, \lambda_3|\lambda_1 = 1) = \frac{p(\lambda_1 = 1, \lambda_2, \lambda_3)}{p(\lambda_1 = 1)}. \]  
(7)

By equation (7), we determine the most probable values of \( \lambda_2 \) and \( \lambda_3 \), which turn out to be almost scale-independent, changing only very mildly in the range of \([0.38, 0.48]\) and \([0, 0.1]\), respectively as the scale \( R_2 \) varies from \( R_G \) to over \( 10 h^{-1} \text{Mpc} \). The values of \( \{\hat{\lambda}_i\}_{i=1}^3 \) can be obtained straightforwardly through equations (3)-(5).
Now, we fit the observational data points obtained in §2 to equation (2) with the value $c$ as an adjustable free parameter. The best-fit value of $c$ is found to be $\langle c \rangle \approx 0.32$ through the $\chi^2$ minimization. Note here that this best-fit value corresponds not to the constant $c_0$ in equation (6) but to the mean value averaged over $R_2$. We also perform an analytic evaluation of the average value, $\langle |\cos \theta| \rangle$ as

$$\langle |\cos \theta| \rangle = \int_0^{\pi/2} |\cos \theta| p(\cos \theta) d\theta.$$ \hspace{1cm} (8)

Now that this average value, $\langle |\cos \theta| \rangle$, is a function of $R_2$ as the correlation parameter, $c$, in $p(\cos \theta)$ depends on $R_2$, we can determine the best-fit value of the constant $c_0$ by fitting the observational data obtained in section §2 to equation (8) with equation (6). We find $c_0 \approx 0.8$.

Figure 2 depicts the analytically derived probability density distribution $p(\cos \theta)$ and the average value $\langle |\cos \theta| \rangle$ as solid lines in the upper and the lower panels, respectively. The comparison with these analytic results with the observational points reveals a fairly good agreement between the two.

4. DISCUSSION AND CONCLUSION

We have presented an observational evidence for the preferential inclinations of the spin axes of the Tully disk galaxies onto the local pancake planes, and provided a quantitative theoretical explanation to the observed phenomena in terms of the tidal interaction and the broken hierarchy.

Successful as the match between the theory and the observation seems, some limitations of our analysis deserve discussing here. First, in the observational analysis the redshift distortion effect is not properly taken into account. Even though the redshift distortion effect is unlikely to reduce the observed inclination strength, as Trujillo et al. (2005) noted, it should be necessary to account for it to find a true signal. Second, in the theoretical analysis, we describe the formation of a local pancake in terms of the Zel’dovich collapse condition. This is an obvious oversimplification of the reality, as Shen et al. (2005) noted that the real collapse condition should be more complicated. Although the Zel’dovich collapse condition is a good approximation, a more realistic description of the formation of a local pancake would be desirable.

Finally, we conclude that our observational and theoretical study of the local pancaking effect on the orientation of the galaxy spin axes will provide a new hint to the unsolved problem of the galaxy formation.
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Fig. 1.— The illustration of a Tully disk galaxy embedded in a local pancake. $\hat{\mathbf{L}}$ represents a spin vector of a galaxy. $R_1$ and $R_2$ are the distances to the two nearest neighbors, respectively. $R_1 \times R_2$ corresponds to a unit normal vector of the local pancake plane. $\theta$ represents the angle between the spin vector and the normal vector of the plane.
Fig. 2.— Upper: the probability density distribution of the cosines of the angles between the galaxy spin axis and the unit vector normal to the local pancake plane. The observational data are plotted as square dots with Poisson error bars. The analytic prediction (eq. [2]) is also plotted as solid line with the best-fit mean value of $\langle c \rangle = 0.32$. The horizontal dotted line corresponds to the case that there is no alignment. Lower: The average value of the cosines of the angles between the galaxy spin axis and the unit vector normal to the local pancake plane as a function of the pancake scale. The squares with the histogram represent the observational result with the Poisson errors. The theoretical prediction (eq. [6]) with $c_0 = 0.8$ is plotted as a solid line. The horizontal dotted line corresponds to the case that