The Spin Alignment of Galaxies with the Large-scale Tidal Field in Hydrodynamic Simulations

Peng Wang1,2, Quan Guo3, Xi Kang1, and Noam I. Libeskind4

1 Purple Mountain Observatory (PMO), No. 8 Yuan Hua Road, 210034 Nanjing, People’s Republic of China; wangpeng@pmo.ac.cn
2 Graduate School, University of the Chinese Academy of Science, 19A, Yuquan Road, Beijing 100049, People’s Republic of China
3 Shanghai Astronomical Observatory (SHAO), Nandan Road 80, Shanghai 20030, People’s Republic of China
4 Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany

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Abstract

The correlation between the spins of dark matter halos and the large-scale structure (LSS) has been studied in great detail over a large redshift range, while investigations of galaxies are still incomplete. Motivated by this point, we use the state-of-the-art hydrodynamic simulation, Illustris-1, to investigate mainly the spin–LSS correlation at z = 0 using hydrodynamical simulations and also provides important insight to understand the formation and evolution of galaxy angular momentum.

Key words: galaxies: evolution – galaxies: general – large-scale structure of universe – methods: observational – methods: statistical

1. Introduction

How the spin of a halo/galaxy is correlated with the large-scale cosmic-web environment is an important question to address for understanding both galaxy formation and the intrinsic alignment of galaxies in the context of weak gravitational lensing. The tidal torque theory (TTT) suggested that there is an alignment between the halo/galaxy spin and the large-scale structure (LSS, Hoyle 1951; Peebles 1969; White 1984; Barnes & Efstathiou 1987), which is often referred to as the spin–LSS correlation. However, the TTT predictions on small scales are affected by the nonlinear evolutions, which may significantly influence the way of mass infall onto halo/galaxy.

In the very first study of N-body simulation by Aragón-Calvo et al. (2007b), who applied a cosmic-web classification called a multiscale morphology filter (MMF, Aragón-Calvo et al. 2007a), they showed that the spin–LSS correlation depends on the halo mass, i.e., the spin of low-mass halos with masses less than $10^{12} h^{-1} M_{\odot}$ are found to be parallel with the direction of the filamentary structure, while a perpendicular signal was found for high-mass halos. Shortly after, Hahn et al. (2007) examined halos in two mass bins (low mass: $5 \times 10^{10} - 10^{12} h^{-1} M_{\odot}$; high-mass: $>10^{12} h^{-1} M_{\odot}$) and claimed a weak anti-alignment for haloes in filaments and a stronger anti-alignment in sheets. With the development of numerical simulations and the improvement of cosmic-web classification (e.g., P-web, T-web, and V-web; for a review, see Libeskind et al. 2018), many studies using dark matter simulations have confirmed the spin–LSS correlations (Zhang et al. 2009; Libeskind et al. 2013, 2014; Trowland et al. 2013; Aragón-Calvo & Yang 2014; Forero-Romero et al. 2014; Pichon et al. 2016; Wang & Kang 2017, 2018; Ganeshiaah Veena et al. 2018).

The above studies have found that the transition halo mass of the spin–LSS correlation ranges from $5 \times 10^{11} h^{-1} M_{\odot}$ to $5 \times 10^{12} h^{-1} M_{\odot}$, which weakly depends on the mass resolution of the simulation and the smoothing scales used to classify the cosmic web. Codis et al. (2012) and Pichon et al. (2016) proposed an empirical formula, where $M_{\text{trans}}^t = M_{\text{trans}}^0 (1 + z)^{-\gamma}$, with $\gamma = 2.5 \pm 0.2$ and where $M_{\text{trans}}^0$ is the transition mass equal to $5(\pm 1) \times 10^{12} M_{\odot}$.

In addition to those works based on N-body simulations, using the hydrodynamic simulation Horizon-AGN, Dubois et al. (2014) investigated the spin–LSS correlation as functions of galaxy properties (such as the stellar mass, color, and star formation rate) in the redshift range of 1.2 < $z$ < 1.8. They claimed that low-mass blue galaxies are preferentially aligned with their nearest filaments, and that high-mass red galaxies show a tendency for a perpendicular signal. They found that the transition mass from alignment to misalignment happens at $\sim 5 \times 10^{10} h^{-1} M_{\odot}$.

These theoretical predictions have to be justified by observations. Using the observational data from Sloan Digital Sky Survey (SDSS) DR8 and the filament finder of the Bisous process (Tempel et al. 2014), Tempel & Libeskind (2013) and Tempel et al. (2013) confirmed that such a correlation depends on the galaxy type, i.e., the spin of spiral galaxies tends to align with their nearest filaments, while the short axes of ellipticals are perpendicular to the filament. Zhang et al. (2015) claimed a mass-dependent correlation where the spins of spiral galaxies have the weak tendencies to be aligned with (or perpendicular to) the intermediate (or minor) axis of the local tidal tensor. Palwa et al. (2016) used the galaxy sample constructed from the 2 Micron All-Sky Survey (2MASS) Redshift Survey (Huchra et al. 2012) and examined the alignment between the galaxy spin and the velocity shear field (V-web, Hoffman et al. 2012; Libeskind et al. 2013). They reported a significant perpendicular signal with respect to the axis of the slowest compression for elliptical galaxies, while no signal was found in spiral galaxies.
A summary of previous investigations is shown in Table 1. Clearly, studies using hydrodynamical simulations and observational data are lagging behind works that use $N$-body simulations.

As can be seen, most works have used $N$-body simulations, and a few have used hydrodynamical simulations and observations. The measurement of a galaxy’s spin and the cosmic-web classification is difficult to observe, and only a few studies are accomplished at a low redshift. Limited by the resolution and cost of hydrodynamics simulations, only a few works investigated the spin–LSS correlation of galaxies at high redshifts. Thanks to the advent of cosmological hydrodynamical simulations, such as Illustris project (Vogelsberger et al. 2014), we can extend the galaxy spin–LSS correlation to the present. This is the main motivation of this work.

The structure of this paper is organized as follow. In Section 2, we will introduce the simulation data, the spin definition, and the cosmic-web classification. In Section 3, we will show the main results. A discussion and the conclusion are presented in Section 4.

### 2. Data and Methodology

The data used in this work were constructed from the state-of-the-art hydrodynamic simulations, Illustris-1, which is the one with the highest resolution simulations and consists of full physics in the Illustris project (Vogelsberger et al. 2014). The Illustris project consists of a set of cosmological hydrodynamic simulations, which are applied by the moving mesh code, AREPO (Springel 2010). The cosmological parameters are consistent with the latest Wilkinson Microwave Anisotropy Probe (WAMP) measurements (Hinshaw et al. 2013), namely: $\Omega_m = 0.2726$, $\Omega_k = 0.7274$, $\Omega_b = 0.0456$, $\sigma_8 = 0.809$, $n_s = 0.963$, and $H_0 = 100h$ km s$^{-1}$ with $h = 0.704$. The Illustris-1 evolves 1820$^3$ dark matter particles and the same number of gas cells from $z = 127$ to $z = 0$ in a volume of a $75h^{-1}$ Mpc wide periodic cosmological box. The mass resolution is $6.26 \times 10^9 h^{-1} M_\odot$ in dark matter and is $2.6 \times 10^8 h^{-1} M_\odot$ in baryonic matter.

The standard Friend-of-Friend (FoF) algorithm (Davis et al. 1985) is used to identify the dark matter halo. The linking length is set to 0.2 times the mean particles separation. In total, 7713.601 FOF groups with more than 32 particles are found in Illustris-1 at $z = 0$. Stellar particles and gas cells were attached to these FOF primaries in a secondary linking stage (Davis et al. 1985). The SUBFIND algorithm (Springel et al. 2001; Dolag et al. 2009) is applied for every FoF group to identify gravitationally bound structures. The halo/galaxy position is defined as the position of the most bound particle of the biggest structure. Galactic properties (such as stellar mass, light, color, etc.) are measured within the radius, $r_s$, which is equal to twice the stellar half-mass radius of each SUBFIND (sub)halo.

In order to make a robust measurement of the galaxy spin, we selected 36,327 galaxies with at least 300 star particles within $30 h^{-1}$ kpc (for comparison, another scale of $15 h^{-1}$ kpc is also considered in our work). The galaxy spin is defined as

$$ j = \sum_{i=1}^{N} m_i r_i \times (\vec{v}_i - \vec{v}), $$

in which $N$ is the total number of star particles within $30 h^{-1}$ kpc ($15 h^{-1}$ kpc), $m_i$ is the mass of the star particle $i$, and $\vec{v}_i$ is the position vector of the star particle $i$ relative to the galaxy center. $\vec{v}$ is the velocity of all star particles within the given scale.

To determine the direction of the LSS around each galaxy, all of the particles (including dark matter, star, and gas particles) are considered. We calculate the Hessian matrix of the smoothed tidal tensor field at the galaxy center, which is define as

$$ T_{ij}(\vec{x}) = \frac{\partial^2 \phi}{\partial x_i \partial x_j}, $$

in which $i, j = 1, 2, 3$ are indices representing spatial dimensions. $\phi$ is the peculiar gravitational potential. By following the commonly used value suggested in previous works on the studies of the halo spin–LSS relation (Aragon-Calvo et al. 2007b; Hahn et al. 2007; Zhang et al. 2009; Codis et al. 2012; Trowland et al. 2013), we set the smoothing length as $R_s = 2 h^{-1}$ Mpc. Notes that in our previous works (Wang & Kang 2017, 2018), we compared several values of $R_s$ and found that there is no significant effect on the halo spin–LSS correlation. The tidal tensor is subjected to a principle component analysis, and its eigenvalues ($\lambda_1 \geq \lambda_2 \geq \lambda_3$) with corresponding eigenvectors ($e_1, e_2, e_3$) are computed. According to the seminal work of the Zel’dovich theory (Zel’dovich 1970), the eigenvector $e_3$ (corresponding to $\lambda_3$) defines the direction of the slowest collapse of mass on a large scale. For instance, for a filamentary environment, $e_3$ is the filament direction, and for a sheet like environments, $e_3$ lies in the sheet plane. In the following analysis, we refer to $e_3$ as the direction of the large-scale tidal field.

To quantify the correlation between the spin of a galaxy with the direction of the LSS, we compute the $\cos(\theta) = j \cdot e_3$ between the galaxy spin vector and $e_3$. Note that we restrict
cos(θ) to be within [0, 1]. In the case where the galaxy spin is randomly oriented relative to $e_3$, the expectation of $\langle |\cos(\theta)| \rangle$ is 0.5; and if $\langle |\cos(\theta)| \rangle$ larger than 0.5, we refer to it as an alignment between the galaxy spin and the $e_3$; if $\langle |\cos(\theta)| \rangle$ smaller than 0.5, it means that the galaxy spin is preferentially perpendicular to $e_3$.

3. Results

In Figure 1, we show the space configuration of the spin–$e_3$ alignment of the galaxies in Illustris-1 at $z = 0$. For clarity, we only show a slice of width that is $2 h^{-1}$ Mpc across the $z$ axis and galaxies with at least 300 star particles within $30 h^{-1}$ kpc (gray circles). Red short lines represent the slowest collapse direction, $e_3$, of the large-scale tidal field. Blue arrows indicate galaxy spins. Generally speaking, the distribution of galaxies shows some filament-like and knot-like structures, and the red short lines generally point along with the filament-like structures and are radially aligned with the knot-like structures. Galaxy spins (blue arrows) show two kinds of trends with respect to the $e_3$: either parallel or perpendicular.

To quantify the spin–LSS correlation, Figure 2 shows the probability distribution of the $\cos(\theta)$, in which $\theta$ is the angle between the galaxy spin measured using star particles within $30 h^{-1}$ kpc and $e_3$ of the tidal field. Galaxies are divided into four bins according to their stellar mass. The upper and lower limit of each bin are $M_1 = [\min(M_\star), 10^8]$; $M_2 = [10^8, 10^{10}]$; $M_3 = [10^{10}, 10^{11}]$; and $M_4 = [10^{11}, \max(M_\star)]$. The mean value of each bin is: $10^{8.58}$ (M1, yellow), $10^{9.40}$ (M2, green), $10^{10.4}$ (M3, blue), and $10^{11.4}$ (M4, red), respectively, in units of $M_\odot$. The black dashed line means that the spin is randomly distributed with the $e_3$. The color regions (with respect to the sample with same color) show the $3\sigma$ spread constructed from 10,000 random uniform distributions with the same size for each sample. To construct the random samples, we kept the $e_3$ fixed and randomized the direction of the galaxy spin. The width of the color regions is inversely proportional to the sample size. In the bottom-left corner, we show the mean value of $\cos(\theta)$, the mean significance ($\langle \sigma \rangle$), and the $p$-value of the Kolmogorov–Smirnov (KS) test, $p_{KS}$. The mean significance and the KS test are performed on the full set of angles to quantify the likelihood that these are consistent with being derived from a uniform distribution. Note that a high value of significance and a low value of $p_{KS}$ indicates a significant signal.

We see that a relatively strong alignment signal is found for low-mass galaxies in M1 (yellow line) with a mean value of $\cos(\theta) = 0.518$, a high value of significance $(\sim 8.0\sigma)$, and $p_{KS} = 2.2 \times 10^{-15}$. The large number of galaxies in this sample results in the high value of significance and the low value of $p_{KS}$. The alignment signal becomes almost randomly distributed in the M2 (green line) sample with a mean value of $\cos(\theta) = 0.501$. However, the two massive samples (M3 in blue and M4 in red) show perpendicular trends, with $\cos(\theta)$ equal to 0.480 and 0.473, respectively. We found that the number of galaxies in those two sample is relative small, leading to a relative small significance and a high $p_{KS}$.

The strength of the alignment (the value of $\cos(\theta)$) decreases with the galaxy stellar mass, which indicates that the spin–LSS correlation of a galaxy changes from a parallel trend at the low-mass end to a perpendicular trend at the high-mass end. This generally agrees with previous simulation works (e.g., Aragón-Calvo et al. 2007b; Hahn et al. 2007; Trowland et al. 2013;...
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Figure 3. Alignment between the galaxy spin and the direction of the large-scale tidal field, \( \mathbf{e}_1 \), as a function of the galaxy property: stellar mass (top panel), \( g-r \) color (middle panel), and 3D shape triaxiality, \( T \) (bottom panel). Blue (green) lines with error bars show the galaxy spin calculated within 30\( h^{-1} \) kpc (15\( h^{-1} \) kpc). Error bars show Poisson errors. Note that the horizontal dashed line corresponds to a random distribution between the galaxy spin and \( T \) of the large-scale tidal field.

Forero-Romero et al. 2014; Wang & Kang 2017, 2018). It also agree, to some extent, with some observational results (e.g., Tempel & Libeskind 2013) under the assumption that spiral galaxies are mainly hosted by low-mass halos and elliptical galaxies are mainly hosted by relatively massive halos.

In order to compare with observational results, we show the impact of galaxy properties (mass, \( g-r \) color, and triaxiality) on the galaxy spin–LSS correlation in Figure 3. As a comparison, two scales (15\( h^{-1} \) kpc in blue lines and 30\( h^{-1} \) kpc in green lines) were used to measure the galaxy spin. Error bars in each panel show the Poisson errors. In panel (a), we show the \( |\cos(\theta)| \) as a function of the galaxy stellar mass, which is similar to Figure 2. Panel (b) shows the \( g-r \) color dependence. Galaxies with low values of \( g-r \) are labeled “blue,” while high values of \( g-r \) are labeled as “red.” In panel (c), galaxy triaxiality is computed by \( T = \frac{a^2 - b^2}{a^2 - c^2} \), in which \( a \geq b \geq c \) are the axes of the galaxy correspondingly measured in the same scale. Purely prolate galaxies have \( T = 1 \), while purely oblate galaxies have \( T = 0 \).

From Figure 3, we found that, in general, the mean of the \( |\cos(\theta)| \) decreases with the value of \( x \)-axis. The transition from alignment to misalignment happen at \( \sim 10^{10.4} \; h^{-1} \; M_\odot \) in the stellar mass, \( \sim 0.62 \) in \( g-r \) color, and \( \sim 0.4 \) in triaxiality. We conclude that: for low-mass, blue, oblate galaxies, their spin tend to align with the slowest collapse direction, \( \mathbf{e}_3 \). However, a perpendicular trend was found in high-mass, red, prolate galaxies. These trends are weakly dependent on the used scales to measure galaxy spin.

The results in Figure 3 show that galaxy spin–LSS correlations are functions of galaxy mass, color, and triaxiality. Usually, the galaxy color and triaxiality are closed to the stellar mass such that low-mass galaxies are more likely to be blue and oblate. Figure 4 we show the distribution of the galaxy stellar mass, color, and triaxiality from the simulation. No strong correlation between them was found. At a given stellar mass, there is a wide range of galaxy color and vice versa. To investigate which is the dominant effect in determining the spin–LSS correlation, in Figure 5 we show the alignment angle \( |\cos(\theta)| \) as a function of color (left panel) and triaxiality (right panel). At each color/triaxiality bin, we divide galaxies into three equal bin (in number) with increasing stellar masses, and we show the signal for the highest/lowest mass bins. Overall, galaxies in the lowest mass bins (blue lines) were always found to have \( |\cos(\theta)| > 0.5 \), indicating an alignment signal, while the highest mass galaxies (red lines) have a misalignment. The trend of this alignment depends weakly on the color and triaxiality. Figure 5 shows that it is the galaxy stellar mass that determines the spin–LSS correlation.

Figure 6 shows the evolution of the spin–LSS alignment at \( z = 1, 2 \). As can be seen, the transition mass decreases with an increasing redshift. The stellar mass transition from alignment...
to misalignment happens around $10^{9.0} h^{-1} M_\odot$ at a redshift of $z = 1$ and around $10^{8.0} h^{-1} M_\odot$ at a redshift of $z = 2$. The evolution trend of the transition value of the stellar mass is consistent with the trend found with dark matter halos (e.g., Wang & Kang 2018). However, it is in conflict with the value suggested by Dubois et al. (2014) of $3 \times 10^{10} h^{-1} M_\odot$ at a redshift of $z = 1.83$. We will discuss this in Section 4.

4. Conclusion and Discussion

In this work, the galaxy spin–LSS correlation at $z = 0$ was investigated using the Illustris-1 hydrodynamic simulation. We have obtained these main results:

1. Our work is the first to investigate the spin–LSS correlation at $z = 0$ using galaxies from cosmological hydrodynamical simulations. We found that, though weak but statistically significant, low-mass galaxies have their spins parallel to $e_3$ and massive galaxies have their spins perpendicular to $e_3$, where $e_3$ is the slowest collapse direction of the large-scale tidal field.

2. The spin–LSS correlation is correlated with the galaxy stellar mass, colors and shape triaxiality. There is a large scatter between the galaxy mass and the color/triaxiality. We find that the stellar mass is the primary effect in determining the spin–LSS correlation.

3. The transition position at a redshift of $z = 0$ from the parallel trend to the perpendicular trend happen at $\sim 10^{9.4} h^{-1} M_\odot$ in the stellar mass, $\sim 0.62$ in the $g-r$ color, and $\sim 0.4$ in triaxiality. The transition stellar mass decreases with the increasing redshifts.

Our results are in broadly consistent with previous results at $z = 0$ using $N$-body simulations (e.g., Aragón-Calvo et al. 2007b; Hahn et al. 2007; Trowland et al. 2013; Forero-Romero et al. 2014; Wang & Kang 2017, 2018; Ganeshaiah Veena et al. 2018). Our results are also the first work that uses model galaxies to verify the conclusion from the observational work (Zhang et al. 2009; Tempel & Libeskind 2013; Pahwa et al. 2016). Additionally, we found that the galaxy spin–LSS alignment is primarily correlated with the stellar mass.

It is worth noting that observational measurement of a galaxy spin is tricky. The spin vectors of spiral galaxies are measured by the R.A., decl., and the inclination angle based on the projected axis ratio (Trujillo et al. 2006; Lee & Erdogdu 2007; Varela et al. 2012). For elliptical galaxies, the projected orientation of the minor axis is used with the assumption that it is aligned with their spin (Tempel & Libeskind 2013). This is not accurate since there is usually a misalignment between the direction of the galaxy spin and the direction of the minor axis.

The origin of the spin–LSS correlation, especially the mass dependence, have promoted many studies in recent years. Some of them (e.g., Aubert et al. 2004; Bailin & Steinmetz 2005; Wang et al. 2005) claimed that the dark matter halo spin
is a result of mergers and the conservation of angular momentum of an accreted mass from a large scale.

Some work (Libeskind et al. 2014; Wang et al. 2014; Shi et al. 2015) found that the mass accretion into halo is universal and that it is mainly along the filament. Such a scenario is able to explain the spin–LSS correlation for massive halo, but it fail to explain for low-mass halos. Kang & Wang (2015) suggested that low-mass halo are preferentially fed by mass perpendicular to the $e_3$ direction and that massive halos are products of major mergers in a filament with mass accretion along the filament direction. This nonuniversal mass accretion (two stage accretion pattern) can well explain the mass dependence of the spin–LSS correlation.

Wang & Kang (2017) also found that the spin–LSS correlation is closely related to the halo formation time and the transition time when the halo environment changes. Wang & Kang (2018) investigated the evolution of the halo spin–LSS correlation in detail by claiming that, at early times, the spin of all halo progenitors is parallel with the LSS and that it evolves to parallel and perpendicular trends at $z = 0$ depending on their mass growth history (Figure 4 in their paper). Dubois et al. (2014) also show a similar picture in the Horizon-AGN simulation (Figure 8 in their paper), while their sample is limited within redshifts from $z = 3.01$ to $z = 1.23$. Therefore, the evolution of the galaxy spin–LSS after $z = 1.23$ is still unknown.

The transition from the parallel trend to the perpendicular trend happens around $10^{10.0} \, h^{-1} M_\odot$ at a redshift of $z = 2$ in this work. However, the transition mass at a redshift of $z = 1.83$, as claimed by Dubois et al. (2014), is around $3 \times 10^{10} \, h^{-1} M_\odot$. The difference may come from the different method of LSS classification and the different physics governing star formation in the hydrodynamic simulation. The transition in the galaxy stellar mass at $z = 0, 1, 2$ from our work is not consistent with the empirical formula proposed by Codis et al. (2012) and Pichon et al. (2016) (see the third paragraph in the Section 1). This indicates that the formation and evolution of the galaxy spin is different with that of the dark matter halo.

It is then interesting to ask how well the spin of a galaxy is correlated with its host dark matter halo and its large-scale cosmic-web environment. The tentative consistency comes with the assumption that the spin of a galaxy is similar to that of its host halo, which does not necessary hold true. The size of a galaxy is typically 10% of the virial radius of its host halo. It is not obvious that the spin of the galaxy, which occupies only the very central part of the halo, should necessarily follow the spin of the entire host halo. For example, Shao et al. (2016) found that the center galaxy is better aligned with the inner 10 kpc of the host halo. Chisari et al. (2017) claimed that the mean misalignment angle between the minor axis of a galaxy and its halo is a strong function of the halo mass, but when the galaxies are divided into disks and ellipticals, there is a significant residual in this relationship. The question then can be rephrased as the follows: should the spin of the inner part of a halo be the same as that of the halo as a whole? This call for more studies, which we will investigate in future work.

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ORCID iDs
Peng Wang https://orcid.org/0000-0003-2504-3835

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