FREQUENT SPIN REORIENTATION OF GALAXIES DUE TO LOCAL INTERACTIONS

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ABSTRACT
We study the evolution of angular momenta of \( M_* = 10^{10} - 10^{12} M_\odot \) galaxies utilizing large-scale ultra-high resolution cosmological hydrodynamic simulations and find that the spin of the stellar component changes direction frequently because of interactions with nearby systems, such as major mergers, minor mergers, significant gas inflows, and torques. The rate and nature of change of spin direction cannot be accounted for by large-scale tidal torques, because the rates of the latter fall short by orders of magnitude and because the apparent random swings of the spin direction are inconsistent with the alignment by linear density field. The implications for galaxy formation as well as the intrinsic alignment of galaxies are profound. Assuming the large-scale tidal field is the sole alignment agent, a new picture emerging is that intrinsic alignment of galaxies would be a balance between slow large-scale coherent torquing and fast spin reorientation by local interactions. What is still open is whether other processes, such as feeding galaxies with gas and stars along filaments or sheets, introduce coherence for spin directions of galaxies along the respective structures.

Key words: cosmology: theory – galaxies: evolution – galaxies: formation – gravitational lensing: weak – methods: numerical

Online-only material: color figures

1. INTRODUCTION
The angular momentum or spin of galaxies is a physical quantity that is far from being fully understood but is of fundamental importance to galaxy formation and cosmological applications. While N-body simulations have shed useful light on the spin properties of dark matter halos (e.g., Vitvitska et al. 2002), it is expected that, given the vastly different scales between the stellar component and dark matter halo component, and the different physical processes governing stellar, gas, and dark matter components, the angular momentum dynamics of galaxies may be quite different and not necessarily inferable from N-body simulations with any reasonable accuracy. We herewith perform a detailed analysis of the dynamics of the spin of galaxies in a full cosmological context, utilizing ab initio LAOZI cosmological hydrodynamic simulations of the standard cold dark matter model (Cen 2014) with an unprecedented galaxy sample size and ultra-high numerical resolution. This paper is the second in the series “On the Origin of the Hubble Sequence.”

2. METHOD
The reader is referred to Cen (2014) for detailed descriptions of our simulations and validations. Briefly, we perform cosmological simulations with the adaptive mesh refinement hydrocode, Enzo (The Enzo Collaboration et al. 2013). The periodic box has a size of 120 h^{-1} Mpc, within which a zoom-in box of a comoving size of 21 \times 24 \times 20 h^{-3} Mpc^3 is embedded. The resolution is better than 114 h^{-1} pc (physical). The cosmological parameters are the same as the WMAP7-normalized (Komatsu et al. 2011) ΛCDM model.

We identify galaxies using the HOP algorithm (Eisenstein & Hut 1998) operating on the stellar particles. A sample of \( \geq 300 \) galaxies with stellar masses greater than \( 10^{10} M_\odot \) are used. For each galaxy at \( z = 0.62 \) a genealogical line is constructed from \( z = 0.62 \) to \( z = 6 \) by connecting galaxy catalogs at a series of redshifts. Galaxy catalogs are constructed from \( z = 0.62 \) to \( z = 1.40 \) with a redshift increment of \( \Delta z = 0.02 \) (corresponding to \( \Delta t = 81 \) Myr at \( z = 1 \)) and from \( z = 1.40 \) to \( z = 6 \) with a redshift increment of \( \Delta z = 0.05 \) (corresponding to \( \Delta t = 80 \) Myr at \( z = 2 \)). The parent of each galaxy is identified with the one at the next higher redshift catalog that has the most overlap in stellar mass.

We compute the specific angular momentum vector \( \mathbf{j}_i \) for stars of each galaxy within a radius \( r \) at each output snapshot \( i \). The time derivative of \( \mathbf{j}_i \) is computed as

\[ \frac{d\mathbf{j}_i}{dt} \equiv \frac{\mathbf{j}_{i+1} - \mathbf{j}_i}{\Delta t_{i+1} - \Delta t_i}. \]  

One notes that due to the finite number of outputs for our simulation data, \( d\mathbf{j}_i/dt \) is somewhat underestimated in cases of rapid changes of angular momentum on timescales shorter than our snapshot intervals. A similar definition for gas is also used. We denote \( t_1 \) as the time required to change the spin vector by \( 1^\circ \) of arc at each snapshot for each galaxy, defined as

\[ t_1 \equiv \frac{\pi}{180} (t_{i+1} - t_i) \arccos(\hat{\mathbf{j}}_{i+1} \cdot \hat{\mathbf{j}}_i), \]  

where \( \hat{\mathbf{j}}_i \) is the unit vector of \( \mathbf{j}_i \). For the first time, we address the evolution of the spin of galaxies statistically in a cosmological setting. All units of length below will be physical.

3. RESULTS
Figure 1 shows the dot product of the unit vector of the specific angular momentum of the central 3 kpc radius stellar region and an arbitrary fixed unit vector as a function of redshift in blue. A significant increase in stellar mass within a short period of time (i.e., mergers), often accompanied by dramatic changes in angular momentum vectors, is visible. We note that the angular momentum vector of a galaxy over its history displays a substantial amount of change even in “quiet” times without major mergers. The ensuing analysis provides some physical insight into this.
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Figure 1. Dot product of the unit vector of the specific angular momentum of the central 3 kpc stellar region and an arbitrary fixed (in time) unit vector as a function of redshift is shown in blue. Each panel shows a random galaxy with its final stellar mass at z = 0.62, indicated at the top of the panel. Also shown in each panel by a red dashed line is the logarithm of the stellar mass with an arbitrary vertical offset.

(A color version of this figure is available in the online journal.)

Figure 2. Top panel: probability distribution function (PDF) of the amplitude of the time derivative of the specific angular momentum of the central 3 kpc radius stellar regions (see Equation (1)) of galaxies with total stellar mass in the range 10^{11}–10^{12} M_☉ in three different redshift ranges, z = 0.62–1 (black histograms), z = 1–2 (red histograms), and z = 2–3 (green histograms), respectively. As an intuitive example, if a Milky Way-like galaxy of size 10 kpc and rotation velocity of 200 km s^{-1} changes its spin direction by 90° in one current Hubble time, it would correspond to a value of log |dj/dt| equal to 2.3 in the x-axis. Middle panel: same as the top panel but for the central 7 kpc radius stellar regions. Bottom panel: same as the top panel but for gas in the central 3 kpc radius region.

(A color version of this figure is available in the online journal.)

The top panel of Figure 2 shows the probability distribution function (PDF) of the time derivative of specific angular momentum of the central 3 kpc radius stellar regions of galaxies with stellar mass in the range 10^{11}–10^{12} M_☉. The middle panel shows the same information as the top panel, except it is for the central 7 kpc radius stellar regions. We see that the overall rate of change of angular momenta is significantly higher at z = 1–3 compared to that at z = 0.6–1. The distribution of |dj/dt| has an extended tail at the high end due to major mergers; due to our finite time sampling these rates are capped by the frequency of our snapshots. Consistent with the expected decline of major merger rate below z ~ 1, the high |dj/dt| tail of the distribution at z = 0.6–1 is significantly less pronounced. No major difference is seen between the 3 kpc and 7 kpc cases,
sugestion that angular momentum changes within the two radii are approximately in tandem and our analysis is robust using 3 kpc. The choice of 3–7 proper kpc is appropriate by noting that a (spiral, elliptical) galaxy of stellar mass $10^{12} \text{M}_\odot$ is observed to have a size of (10.8, 15.1) kpc (Shen et al. 2003) for low-redshift galaxies. The size roughly scales with the root of the stellar mass and decreases with increasing redshift (e.g., Trujillo et al. 2006).

The bottom panel of Figure 2 shows the PDF for gas in the central 3 kpc radius region. We see that the specific angular momenta of the gas within the central 3 kpc change at rates 5–10 times higher than that of stars (top panel of Figure 2). There is no doubt that gas inflows contribute significantly to the change of the stellar angular momentum in two ways. First, significant gas inflows at angles inclined to the stellar mid-plane may torque the stars (and vice versa). Second, new gas that reaches there will form new stars that have a different angular momentum vector and cause the overall angular momentum to change in both direction and magnitude. At high redshift the orientation of the gas inflows on large scales are not well correlated with that of the stars or gas already there. Since the amount of gas tends to be smaller than the stars, it is easier to alter the angular momentum of the gas than that of the stars. In the absence of major mergers, we expect minor stellar mergers could also alter the angular momentum vector.

Figure 3 shows the CPDF of the time to change the direction of spin of the central 3 kpc radius stellar region by 1$^\circ$ of arc, which is dependent on mass and redshift (top panel), environment (middle panel), and galaxy type (bottom panel).

Consistent with Figure 2 we see that the frequency of the spin direction change increases with redshift; the median $t_1$ decreases by 60%–80% from $z = 0.62–1$ to $z = 2–3$, with the higher mass group corresponding to the high red end of the range of frequency of spin changes. The median $t_1$ decreases by 10%–20% from $M_* = 10^{10–12} \text{M}_\odot$ to $M_* = 10^{10–11} \text{M}_\odot$ with the mass dependence somewhat stronger at low redshift than at high redshift. That less massive galaxies tend to experience more rapid changes of specific angular momenta is anecdotally apparent in Figure 3. We also find a large misalignment between the inner stellar (and gas) regions and the outer halos (not presented here), in broad agreement with the conclusions of Hahn et al. (2010).

A dependence on environment is seen in the middle panel, with the median $t_1$ decreasing by a factor of 1.9–2.7 from $\delta_{0.5} = 1–10$ to $\delta_{0.5} = 10^2–10^3$; the environment dependence weakens at higher redshift. The finding that the spin direction of galaxies changes more frequently in dense environments can be attributed to enhanced local interactions there. In the bottom panel, the dependence on galaxy type gives mixed trends. For blue ($g – r < 0.60$) galaxies the median $t_1$ decreases steadily from $z = 2–3$ to $z = 0.62–1$ by a factor of $\sim 2.3$, whereas for red ($g – r > 0.60$) galaxies the median $t_1$ hardly changes from $z = 2–3$ to $z = 0.62–1$. The median $t_1$ for red galaxies is comparable to that of blue galaxies at $z = 2–3$; at lower redshift the median $t_1$ for red galaxies becomes progressively lower compared to that of blue galaxies, mainly due to the latter increasing with decreasing redshift. In Cen (2014), we show that the vast majority of red galaxies do not gain significant stellar
mass in the red sequence. Thus we conclude that the rapid change of spin direction for red galaxies are due to torques by nearby galaxies, whereas blue galaxies are subject to all three local interactions—gas accretion, stellar accretion, and torques.

It is instructive to put the frequency of spin direction change into some perspective. For a point mass $M$ at a distance $d$, the torque of $M$ on a galaxy with a quadrupole moment $Q$ and angular momentum $J$ is $\tau = (3/4)GMQ/d^3 \sin(2\theta)$ (e.g., Peebles 1969), where $\theta$ is the angle between the separation vector and the symmetry axis of the galaxy. Expressing $\tau$ in terms of the overdensity $\delta$ of the region centered on mass $M$, $\tau = \pi G \rho_0 (1 + z)^3 \delta Q \sin(2\theta)$, where $z$ is the redshift and $\rho_0$ the mean mass density at $z = 0$. We approximate spirals as flat axisymmetric uniform disks with $a = b = \infty c$ (giving the quadrupole moment of $Q = 2ma^2/5$) and full rotation support. This allows us to express the torque time $t_q$, defined to be the time taken to change the spin direction by $1^\circ$ of arc,

$$t_q = \frac{\pi |j_\ast|m}{180 \tau(z, m, T)},$$

(3)
giving $t_q = 2.5$ Gyr for $\delta = 200$, $z = 1$, and $\sin(2\theta) = 1$ for spiral galaxies. Comparing to the median $t_1 \sim 10^{-3} - 10^{-2}$ Gyr seen in Figure 3, it is evident that the rapid spin reorientation of galaxies cannot possibly be due to tidal torques by large-scale structure. It is noted that the intrinsic alignment caused by a primordial large-scale gravitational field is inconsistent with the frequent directional change shown in Figure 1.

Under the (unproven) assumption that the large-scale tidal field is the sole alignment agent, any alignment between galaxies on large scales would result from a balance between the fast reorientation rate due to local processes and slow coherent torques by large-scale structure, which is expressed as the ratio $t_1/t_q$, denoted as $t_1/t_q + t_q$. If the quadrupole of the galaxy is, in this case, produced by local interactions, independent of the large-scale tidal field, the alignment in this simplified model would be linear (instead of quadratic; see Hirata & Seljak (2004)) to the large-scale gravitational tidal field. We finally obtain the expression for the mean value of $\eta(t_1)$, shown in Figure 3, and denoted as $\eta(z, m, T)$:

$$\eta(z, m, T) \equiv \int \left( \frac{t_1}{t_1 + t_q(z, m, T)} \right) P_{z, m, T}(t_1) dt_1,$$

(4)

at redshift $z$ for galaxies of mass $m$ and type $T$ (spiral or elliptical). We approximate elliptical galaxies as oblate axisymmetric spheroids with $a = b = 2c$ and $v_{\text{eq}}/\sigma = 0.2$, resulting in the quadrupole moment of $Q = 3ma^2/10$. The sizes of galaxies are adopted from observations by Shen et al. (2003). The bias factor is from Tegmark et al. (2004) adjusted to $\sigma_8 = 0.8$. The stellar mass to light ratio as a function of absolute magnitude is taken from Kauffmann et al. (2003). We incorporate these into $\tau$ to obtain

$$\tau(z, m, T) = \pi G \rho_0 (1 + z)^3 D_\ast(z) b(m) Q(m, T) [\delta \sin(2\theta)]$$

(5)
as well as into $j$ in Equation (3) for different galaxy types, where $D_\ast(z)$ is the linear density growth factor normalized to unity at $z = 0$ and $b(m)$ is the bias factor of galaxies of mass $m$.

The results using Equation (4), in conjunction with Equations (3) and (5), are shown in Figure 4. As in the linear alignment model (e.g., Catelan et al. 2001), the difficulty is in defining a demarcating scale between local and linear large-scale structures. We tentatively have left the scalings to be relative, absorbed into $[\delta \sin(2\theta)]$. If compelled to give an estimate relevant to weak lensing, one might choose $[\delta \sin(2\theta)]$ to be in the range 1–10. In this case, we get a tangential shear $\gamma_T$ that is 1–10 times $\eta$ in Figure 4, resulting in $\gamma_T$ of $-0.2$–2% for the most massive elliptical galaxies (i.e., luminous red galaxies, LRGs, red dots in Figure 4), which, coincidentally, falls in the range of the observed GI (galaxy gravitational tidal field) signal for LRGs (e.g., Mandelbaum et al. 2006; Hirata et al. 2007; Joachimi et al. 2011). The negative sign comes about because the galaxies, under the torque of a central mass, have a tendency to align their disks in the radial direction that is dynamically stable.

Three separate trends with respect to $z$, $m$, and $T$ are seen: the alignment (1) decreases with increasing redshift, (2) decreases with decreasing stellar mass, and (3) is larger for elliptical galaxies than for spiral galaxies. The first two trends are accounted for by the trends of $t_1$ seen in Figure 3. The last trend requires some discussion. The bottom panel of Figure 3 shows that ellipticals have shorter $t_1$ than spirals, due in large part to their residing in overdense environments and in addition to their having a lower overall specific angular momentum amplitude. However, because the specific angular momentum of ellipticals is a factor of five lower than that of spiral galaxies, elliptical galaxies are easier to slew.

It is arguably relatively more straightforward to compare observations of (radial) alignments of satellite galaxies with respect to the central galaxies of groups and clusters. This is however complicated by (at least) four issues. First, the observed detection and non-detection of radial alignment of galaxies around groups and clusters of galaxies concern radial ranges that are already mostly in the nonlinear regime (i.e., overdensity $\delta \gg 1$). Second, most of the observed galaxy samples analyzed contain of the order of 100–10,000 galaxies, hence statistical uncertainties are in the range of 1%–10%. Third, the observed samples likely contain a large number of projected galaxies with physical
separations that are much larger than their lateral distance from the cluster/group center; the degree of projection effects is strongly dependent on the orientation of the line of sight (e.g., viewing a cluster along a filament) and significantly complicates the interpretation of the results. Fourth, on some very small scales, binary interactions between a satellite and the central galaxy may play a dominant role. A combination of these factors may explain the current confused state with conflicting observational results (e.g., Bernstein & Norberg 2002; Pereira & Kuhn 2005; Agustsson & Brainerd 2006; Tolotina et al. 2007; Faltenbacher et al. 2007; Hao et al. 2011). Nonetheless, we expect the radial alignment, if it exists, to decrease with increasing redshift, which is perhaps already hinted at by some observations (e.g., Hung & Ebeling 2012), and with decreasing cluster mass at a fixed radius.

The simple model presented has two notable caveats. First, it assumes that the only alignment mechanism is gravitational torque by some large-scale structure. So far we have presented only the relative scalings among different galaxies under this assumption, but not the absolute magnitude. We cannot justify this rather critical assumption with confidence at this time. Second, one notes that a significant portion of the galaxy spin direction reorientation is likely due to gas feeding and substructure merging. Thus, it is not unreasonable to expect that the gas feeding and substructure merging have some preferred directions, such as along the filaments and sheets. In this case, while the galaxy spin direction changes frequently as shown here, it may do so with some degree of coherence over some scales (such as the scale of filaments), either contemporaneously or through long-term memory of large-scale structure (e.g., Libeskind et al. 2012). If this were true, it then suggests that intrinsic alignments may be a result of balance between high-frequency random reorientation at short timescales and some sort of large-scale “mean” feeding pattern on long timescales. There is some empirical evidence for galaxies to be aligned with large-scale structures in a sense that is consistent with this “feeding” picture (e.g., Zhang et al. 2013; Li et al. 2013). It should be a priority to understand this issue systematically.

4. CONCLUSIONS

Utilizing ab initio Large-scale Adaptive-mesh-refinement Omniscient Zoom-In cosmological hydrodynamic simulations (LAOZI Simulation) of the standard cold dark matter model, we study the evolution of the angular momenta of massive \( M_\ast \leq 10^{10–10^{12}} M_\odot \) galaxies. The simulation has an ultra-high resolution of \( \leq 114 \) pc \( h^{-1} \) and contains more than 300 galaxies with stellar mass greater than \( 10^{10} M_\odot \). We find that the spin of the stellar component changes direction frequently, caused by interactions with nearby systems, such as major mergers, minor mergers, significant gas inflows, and torques, with the median time of the directional change of the spin vector by \( 1^\circ \) of arc in the range 1–10 Myr. The spin of the gas component changes with rates that are a factor of 5–10 higher than those of the stellar component. Because the processes that are responsible are mostly in the nonlinear regime, we do not expect the findings to significantly depend on precise cosmological parameters.

The rate of change of the spin direction cannot be accounted for by large-scale tidal torques because the rates of the latter fall short by two to three orders of magnitude. In addition, the nature of change of the spin direction—apparent random swings—is inconsistent with alignment due to the linear density field. A new paradigm emerging with respect to the intrinsic alignment of galaxies is that it is determined, primarily, by a balance between slow large-scale coherent torquing (if it were the sole alignment process) and fast spin reorientation by local interactions. This suggests that a significant revision to the large-scale tidal-torque-based alignment theory is perhaps in order. The simple analysis presented here indicates that intrinsic alignment of galaxies is dependent on redshift, luminosity, environment, and galaxy type. Specifically, it is found that the alignment (1) decreases with increasing redshift, (2) decreases with decreasing stellar mass, and (3) is larger for elliptical galaxies than for spiral galaxies. While no detailed comparisons are made, the trends found appear to be broadly consistent with and thus provide the physical basis for the observed trends.

What remains open is whether other processes, such as feeding galaxies with gas and stars along filaments or sheets, introduce some coherence of their own kind to the spin direction of galaxies along the respective structures. This will require a separate study with greater detail.

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