Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **404,** 975–980 (2010) doi:10.1111/j.1365-2966.2010.16336.x

Galaxy Zoo: a correlation between the coherence of galaxy spin chirality and star formation efficiency*

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Accepted 2010 January 11. Received 2009 December 4; in original form 2009 June 9

ABSTRACT

We report on the finding of a correlation between the past star formation activity of galaxies and the degree to which the rotation axes of neighbouring galaxies are aligned. This is obtained by cross-correlating star formation histories, derived using the multiple optimized parameter estimation and data compression (MOPED) algorithm, and the spatial coherence of spin direction (chirality), as determined by the Galaxy Zoo project, for a sample of Sloan Digital Sky Survey (SDSS) galaxies. Our findings suggest that spiral galaxies, which formed the majority of their stars early ($z > 2$), tend to display coherent rotation over scales of $\sim$10 Mpc h^{-1}. The correlation is weaker for galaxies with significant recent star formation. We find evidence for this alignment at more than the 5σ level, but no correlation with other galaxy stellar properties. This finding can be explained within the context of hierarchical tidal-torque theory if the SDSS galaxies harbouring the majority of the old stellar population were formed in the past, in the same filament and at about the same time. Galaxies with significant recent star formation instead are in the field, thus influenced by the general tidal field that will align them in random directions, or have had a recent merger that would promote star formation but change the spin direction.

Key words: galaxies: general – cosmology: theory.

1 INTRODUCTION

In our progress to understand how galaxies have formed and evolved, it has recently become clear (e.g. Jimenez et al. 2008) that the present stellar mass of galaxies determines most galaxy properties. It is thus possible to predict, on average, what star formation, metallicity, environment, etc., a galaxy has by simply measuring its current stellar mass. However, there are second-order differences among the properties of galaxies with the same stellar mass and these need to be explained. One of the most obvious physical mechanisms to explain this second parameter is the spin of the dark matter halo. It is now 60 years since Hoyle's seminal paper on the subject (Hoyle 1949), which showed how angular momentum in galaxies can be generated via the tidal field of other galaxies. Later, Doroshkevich (1970) developed the tidal-torque theory within the framework of hierarchical galaxy formation, which determines the amplitude and direction of the spin of a dark matter halo based on the surrounding dark matter field (see Schaefer 2008 for a

*This publication has been made possible by the participation of more than 100 000 volunteers in the Galaxy Zoo project. Their individual contributions are acknowledged at http://www.galaxyzoo.org/Volunteers.aspx.
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recent review). Numerical *N*-body simulations produce results that are in good agreement with the theoretical predictions, although linear theory is not always sufficient to determine the final angular momentum of a collapsed object (e.g. Barnes & Efstathiou 1987; Porciani, Dekel & Hoffman 2002 and references therein). In addition, mergers are expected to significantly alter a halo final spin (Hetznecker & Burkert 2006).

The amplitude of the dark matter halo spin will influence the radius where baryons will settle into a disc (White & Rees 1978; Fall & Efstathiou 1980), thus influencing its density and therefore the star formation history of the galaxy. The influence of spin on star formation history has been studied in detail (Toomre 1964; Dalcanton, Spergel & Summers 1997; Jimenez et al. 1997; Mo, Mao & White 1998; Avila-Reese, Firmani & Hernandez 1998).

One interesting feature of tidal-torque theory in hierarchical models (Heavens & Peacock 1988; Catelan & Porciani 2001; Catelan, Kamionkowski & Blandford 2001; Crittenden et al. 2001; Porciani et al. 2002; Hahn et al. 2007) is the prediction of correlated spin directions and that the spin direction for dark haloes is strongly influenced by the halo environment. Pen, Lee & Seljak (2000) reported a detection of galaxy spin correlations at 97 per cent confidence. Slosar et al. (2009) have measured the correlation function of the spin chirality and report, for the first time, a signal at scales $<0.5\,\mathrm{Mpc}\,h^{-1}$ at the 2–3 σ level. This subject has received renewed interest not just for being a test of tidal-torque theory but because the mechanism that produces angular momentum alignment is believed to create correlations between observed galaxy shapes, introducing a potential contamination to the cosmological weak lensing signal.

Observationally, it is very difficult to obtain full information on the spin vector of a dark matter halo. Concentrating on disc galaxies, the plane of the disc determines the axis of rotation of the disc of baryonic matter. For galaxies seen in projection, the observed galaxy ellipticity constrains the galaxy spin axis. For infinitely thin and perfectly circular discs, the spin vector axis would be known but not the spin 'chirality' (the spin direction along the axis). For realistic discs, projection effects mean that what can be measured reliably is the projected spin axis. Information about the spin chirality is absent in the study of galaxy ellipticity. Nevertheless, chiral information is known for the sample of face-on galaxies of the Galaxy Zoo project.[1] The correlation of chirality therefore implies a correlation of the spin vectors.

An expectation of tidal-torque theory is that haloes that formed together, and thus experienced a similar tidal field during their initial collapse, will have similarly aligned spin vectors. Galaxy chirality should thus be coherent on scales related to those of large-scale structure.

Here, we explore whether spatially coherent spin chirality (and therefore spin vectors) correlate with other galaxy properties that depend on the galaxy stellar population and star formation history. Our main finding is that the absolute value of the average spin direction of the galaxies located in a spatial patch (pixel) is correlated with past star formation activity in these galaxies. However, we find no correlation with other galaxy properties such as metallicity, or with the average spin itself (i.e. the Universe does not have a preferred direction). The rest of the paper is organized as follows. In Section 2 we describe the galaxy sample selection and the methodology, in Section 3 we present the results, and in Section 4 we present some discussion and draw our conclusions.

[1] http://www.galaxyzoo.org

2 SAMPLE SELECTION AND METHOD

In the Galaxy Zoo project, a sample of 893 212 galaxies was visually classified by about 90 000 users. The sample galaxies were selected to be sources that were targeted for SDSS spectroscopy (i.e. extended sources with Petrosian magnitude $r < 17.77$). Additionally, we have included objects that were not originally targeted as such, but were observed to be galaxies once their spectrum was taken. Where spectroscopic redshifts were available, we found that galaxies have the mean redshift of $z = 0.14$ and the objects with the highest redshift reach $z \sim 0.5$. The galaxies thus probe our local Universe at cosmological scales. Each object has been classified about 40 times from a simplified scheme of six possible classifications: an elliptical, a clockwise spiral galaxy, an anticlockwise spiral galaxy, an edge-on spiral galaxy, a star/unknown object, a merger. Various cuts (hacking attempts, browser misconfigurations, etc.) removed about 5 per cent of our data. The data were reduced into two final catalogues based on whether data were weighted or unweighted. In the unweighted data, each user's classification carried an equal weight, while in the weighted case, a user's weights were iteratively adjusted according to how well each user agreed with the classifications of other users. In both cases, the accrued classifications were further distilled into 'super-clean', 'clean' and 'cleanish' catalogues of objects, for which we required 95, 80 and 60 per cent of users, respectively, to agree on a given classification. In all cases, this is a statistically significant classification with respect to random voting; however, the human 'systematical' error associated with it is difficult to judge. In any case, we are in the limit where taking more data will not change our sample beyond noise fluctuations as the votes are uncorrelated. A detailed account of the reduction procedures as well as the procedure to measure spin orientations, and the removal of systematics, can be found in Lintott et al. (2008) and Land et al. (2008).

We consider the sample of spiral galaxies of the Galaxy Zoo project for which the spin chirality (i.e. the direction of the galaxy arm winding) has been determined. This piece of information for each galaxy is what we refer to as halo spin chirality. In general, the gas of a galaxy should be rotating in the same direction as the halo; about 4 per cent of the galaxies do not do this (Pasha & Smirnov 1982), but there should be a strong – although not perfect – correlation between the angular momentum vector of gas and that of the dark matter halo hosting a galaxy (van den Bosch et al. 2002). Here, we assume that the chirality of the galaxy is a proxy for the rotation direction of the host dark matter halo.

Our catalogue of galaxy star formation properties is obtained from Panter et al. (2007). This catalogue has been constructed from the spectroscopic main galaxy sample of the SDSS data release 4 (Adelman-McCarthy et al. 2006). Star formation histories, metallicities, stellar masses and dust content have been extracted using the multiple optimized parameter estimation and data compression (MOPED) algorithm (Heavens, Jimenez & Lahav 2000a), which allows for rapid extraction and parameter exploration of galaxy spectra using stellar population models. The method has been explored in detail in Panter et al. (2007) and has been tested with the versatile spectral analysis (VESPA) algorithm (Tojeiro et al. 2007) for accuracy and extent of degeneracies in the recovered parameters (see Panter et al. 2007 and Tojeiro et al. 2007 for details). The star formation histories catalogue from VESPA (Tojeiro et al. 2009) is available on-line.[2] Although for the SDSS spectra,

[2] http://www-wfau.roe.ac.uk/vespa/

individual star formation histories are poorly constrained (Tojeiro et al. 2007) because of the low signal-to-noise (S/N), the sample of average properties is robust and well constrained; it is these average quantities that we use in our study. Panter et al. (2007) give a thorough and detailed explanation of the method, its shortcomings and advantages, and we refer the interested reader to this paper for a detailed description of the star formation catalogue used in the present work. The catalogue contains about half a million galaxies.

To create our final sample we match the above two catalogues, MOPED and Galaxy Zoo (keeping only galaxies that are classified as clean), to obtain a total of 12 897 galaxies at redshift $z < 0.2$. The redshift distribution of our sample is narrow (the redshift interval $0.012 < z < 0.13$ encloses 90 per cent of the galaxies, and the maximum of the redshift distribution is $z_{\rm m} = 0.08$). It is this sample that we use in our study. Note that the galaxies in the sample are spirals, and therefore the downsizing effect is not as extreme as in ellipticals.

We uniformly pixelize the survey using a range of pixel sizes. In what follows, we use a flat concordance lambda cold dark matter (LCDM) model to convert between redshifts and distances. In each pixel, we define a pixel spin chirality S_j given by the average spin chirality for the galaxies in the pixel

$$S_j = \sum_{i=1}^{N_j} s_i / N_j ,$$

where N_j denotes the number of galaxies in pixel j and s_i denotes a galaxy spin chirality; s_i can only take values of +1 or −1 while $-1 < S_j < 1$. For uncorrelated spin direction, within the errors $S_j = 0$, only for correlated spin direction, the average spin chirality will be significantly non-zero (see Fig. 1). Note that when we compute the cross-correlation of galaxy quantities with the pixel spin chirality S_j, we use the absolute value, $|S_j|$. We show that there is no correlation when we use the full value of S_j (including its sign).

Each galaxy in the sample (index i) has associated with it a stellar mass, a metallicity, a metallicity history and a star formation history. The star formation history is described by the star formation in independent bins (index β), $\psi_{\beta,i}$: nine equally spaced in look-back time and two bins for high-redshift star formation (see Table 1). For each galaxy, the star formation is normalized to unity. For each pixel, we also define a deviation from the mean star formation history given by the average star formation in each bin over the pixelgalaxies minus the global average star formation:

$$SF_{j,\beta} = \sum_{i=1}^{N_j} \psi_{\beta,i} / N_j - \langle \psi \rangle .$$

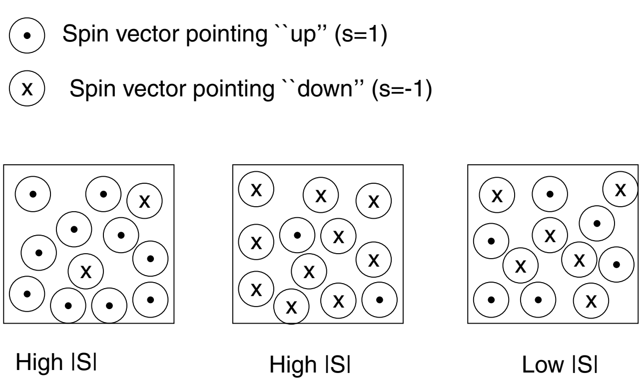

Figure 1. Graphical depiction for a given pixel size of what it means to have a high value of s_j.

Table 1. Centre and boundaries [(l)ower, (c)entre, (u)pper] of the star formation bins in redshift (z) and look-back time $t_{\rm lb}$ in Gyr.

Bin	l z	c z	u z	l $t_{\rm lb}$	c $t_{\rm lb}$	u $t_{\rm lb}$
11	0.0007	0.001	0.00145	0.00966	0.014	0.0200
10	0.00145	0.0021	0.003	0.0200	0.029	0.0414
9	0.003	0.006	0.0063	0.0414	0.06	0.0857
8	0.0063	0.012	0.013	0.0857	0.12	0.1776
7	0.013	0.0179	0.027	0.1776	0.26	0.3677
6	0.027	0.0419	0.057	0.3677	0.53	0.7614
5	0.057	0.0839	0.125	0.7614	1.10	1.5767
4	0.125	0.186	0.287	1.5767	2.27	3.2650
3	0.287	0.456	0.786	3.2650	4.70	6.7609
2	0.786	1.200	2.000	6.7609	8.46	10.32
1	2.000	4.000	8.000	10.32	12.09	13.00

Metallicity history is treated in the same way. Note that by comparing average quantities in each pixel rather than total quantities we are not directly sensitive to the galaxy local density. Correlation between chirality and density has been explored in Land et al. (2008).

Therefore, we have several pixelized maps: a map of spin chirality, and 24 maps of galaxy star formation properties (stellar mass, metallicity, 11 maps of star formation at different look-back times, and similarly 11 maps for metallicity history).

To quantify a possible correlation between galaxy properties and spin coherence, we use the Pearson correlation coefficient and explore how it varies as a function of pixel size, lag and star formation properties. Errors are estimated by repeating the procedure with randomized spins. This cross-correlation in pixels of a finite size essentially contains information on the integrated cross-correlation function below some pixel size. If certain properties correlate in two-point statistics up to a certain scale, our statistical test will pick it up.

3 RESULTS

We are interested in exploring whether galaxies with a particular property have their spins aligned or randomly oriented with respect to their neighbours. In this respect, we do not need to worry about projecting the spin vector on a common reference frame for all galaxies, as was done by Land et al. (2008) and Slosar et al. (2009), as we are only interested in the cross-correlation between the spatially averaged chirality of the galaxies and their star formation properties. We also interpret the chirality of the galaxy spin as a proxy for the halo spin chirality.

The spins of the galaxies in our sample are spatially correlated (Slosar et al. 2009) and the star formation properties are also spatially correlated with the large-scale cosmological structures (e.g. Sheth et al. 2006). The cross-correlation as defined in Section 2 indicates which galaxy property is mostly correlated with the large-scale tidal field responsible for spin alignment.

We find no correlation of the absolute value of the pixel spin chirality with stellar mass, metallicity or metallicity history but we find significant correlation with star formation history. Further, when we correlate the pixel spin chirality (not its absolute value but keeping the sign) with the star formation history, we find no correlation. To be precise, the Pearson coefficient we find is of the order of 4 per cent at all look-back times, which is below the error in the coefficient itself (see below).

Fig. 2 shows the relation between the pixel-averaged star formation fraction ($SF_{j,1}$) in the oldest MOPED bin (1; see Table 1) and

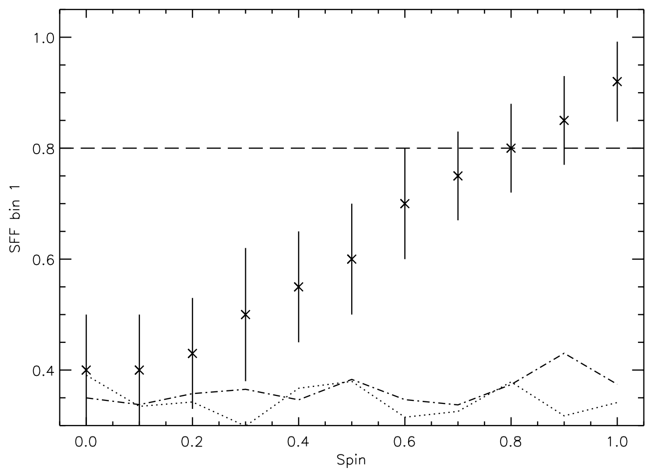

Figure 2. Relation between pixel-averaged star formation fraction in the oldest MOPED bin (1; see Table 1) and pixel-averaged absolute spin $|S_j|$ (for a pixel size of 10 Mpc h^{-1}) for all those galaxies that have formed more than 30 per cent of their present stellar mass at $z > 2.0$. Because of the large number of pixels, instead of showing a scatter plot we show the mean relation; error bars show the standard deviation around the mean relation. Note that spiral galaxies that formed more than 30 per cent of their stars at $z > 2$ have preferentially a coherent spin chirality. If we focus on those spiral galaxies that formed more than 80 per cent (denoted by the dashed line) of their stars at $z > 2$, then virtually all of them have coherent spin chirality. The dotted and dash-dotted lines show the pixel-averaged star formation but for choices of the pixel size of 2 and 50 Mpc h^{-1}, respectively. For these cases, the value of the star formation fraction as a function of absolute spin is consistent with zero, as error bars are similar to the 10 Mpc h^{-1} pixel-size case and are not plotted for clarity (see text for more details).

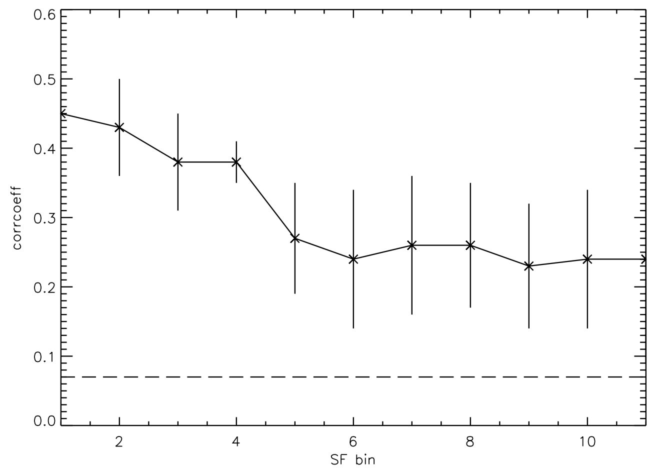

Figure 3. Pearson correlation coefficient between the absolute value of pixel spin chirality and past star formation as a function of the start formation in look-back time bin number (see Table 1 for conversion between bin number and look-back time). The pixel size is 10 Mpc h^{-1}. The points are the mean of the correlation coefficient for several redshift slices. Error bars show jack-knife estimates of the correlation coefficient rms by using several redshift slices. The dashed line shows the 1σ correlation level obtained with a randomized spin map. Galaxies with star formation in the oldest bins (1–3) show strong correlation with spin chirality (and therefore with spin alignment). The correlation decreases for galaxies with more recent star formation.

the absolute value of the pixel-averaged spin $|S_j|$ for all those galaxies that have formed more than 30 per cent of their present stellar mass at $z > 2.0$. Because of the large number of pixels, a scatter plot is unclear; here, the points indicate the mean relation and the error bars show the standard deviation around the relation. Note that spiral galaxies that formed more than 30 per cent of their stars at $z > 2$ have preferentially a coherent spin chirality. If we focus on those spiral galaxies that formed more than 80 per cent (denoted by the dashed line) of their stars at $z > 2$, then virtually all of them have coherent spin chirality. This implies that those galaxies that were in place at $z > 2$ rotate on the same direction on scales of ∼10 Mpc.

To quantify our results, we find that the Pearson correlation coefficient between the absolute value of the pixel spin chirality and past star formation maps is maximum at zero-lag for a physical pixel size of ∼10 Mpc h^{-1}. For smaller pixel sizes (<2 Mpc h^{-1}), the number of galaxies per pixel decreases very rapidly. The correlation disappears for pixel sizes larger than ∼50 Mpc h^{-1}. See also Fig. 1, where we show the value of the correlation for different pixel sizes.

We find that the correlation is greatest for galaxies that formed most of their stars in the past and decays for galaxies with most of their stars being formed recently.

Fig. 3 shows the Pearson correlation coefficient for the absolute value of the pixel spin chirality as a function of the star formation bin (see Table 1). The points have been obtained by computing the mean for several redshift slices of width ∼100 Mpc, and the error bars shown are from the mean dispersion in the different, ∼10, redshift slices. The dashed line shows the error in the correlation coefficient obtained from randomly redistributing the values of the $|S_j|$ map. We can see that for those galaxies with significant star formation in the oldest bins (1–4) the correlation with absolute value of pixel spin chirality is 6σ above the noise level, while it decreases to slightly weaker levels for galaxies with significant star formation in their recent bins (8–11). This finding indicates that spiral galaxies with most of their star formation in the past have most of their galaxies rotating in the same direction with a coherence length of 10 Mpc h^{-1}. To explore the correlation for separation smaller than 10 Mpc h^{-1}, we have repeated the analysis with the projected catalogue. The catalogue depth implies that in the line-of-sight direction the cell size, R is always ∼343 Mpc h^{-1}, thus diluting the signal if the signal coherence length is smaller than R. The higher density of objects, however, enables us to explore smaller separations. We find that the signal is maximal for cell sizes of 10 Mpc h^{-1} (given by the transversal cell size at $z_{\rm m}$) and decreases rapidly for cell sizes greater than 50 Mpc h^{-1}. As before, also in this case when considering the full value of the pixel spin chirality (i.e. keeping the sign), we obtain no statistically significant correlation.

These results indicate that the Universe does not have a preferred direction and/or, more importantly, that human biases in classifying the rotation direction do not enter into our analysis.

Table 2 shows, for the 11 look-back times, the percentage deviation from zero in the value of the pixel spin chirality when we consider the sign. It is demonstrated that a small bias at the 3–4 per cent level remains, towards negative values of S but below the intrinsic error. To calculate the values of the bias in each

Table 2. Per cent deviation in each look-back time star bin for the quantity $|S_j|$ from zero, which means the Universe has no preferred direction. Note that there is a negative bias at the per cent level, but this error is below the error from the correlation analysis (see text).

SF bin	11	10	9	8	7–1
Per cent	−0.7	−2.5	−3.4	−2.9	−3.8

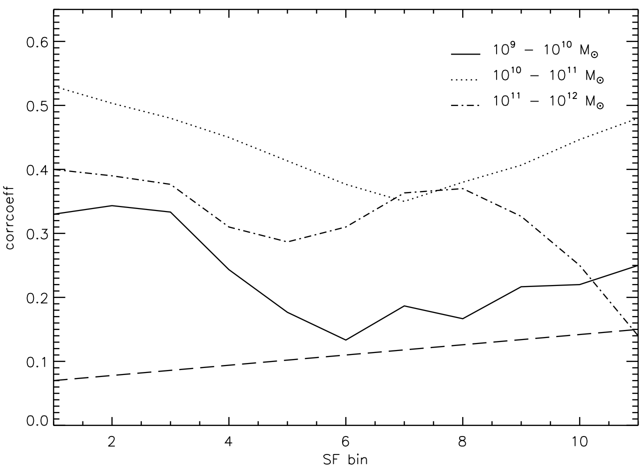

Figure 4. Same as Fig. 3 but for three different mass ranges. In this case, we use the projected map in order to increase the signal-to-noise. Note that the signal at bins 1 and 2 is dominated by galaxies in the mass range 10^{10}–10^{11} M$_\odot$.

look-back time bin, we calculate $\sum S_\beta$ for all the galaxies in that bin that contribute to more than 90 per cent of the bin star formation. We have also verified that the strength of the correlation signal does not depend on how many galaxies are included in the sample by randomly subsampling the catalogue; the error bars, of course, increase when fewer galaxies are considered.

Because star formation is also correlated with mass (Sheth et al. 2006), we explore whether the above correlation is driven by the mass of the galaxy. MOPED provides the present and total stellar mass in the galaxy. In Fig. 4 we show the above correlation but for three mass ranges. The dashed line shows the correlation level for a map where the absolute values of pixel spin chirality have been redistributed randomly; therefore, it is a measure of the noise level. We note that the correlation at early times (bins 1 and 2) is dominated by galaxies in the mass range 10^{10}–10^{11} M$_\odot$. (Recall that because the sample is approximately volume-limited the number of galaxies in each of the mass bins decreases rapidly with increasing mass, so the trend is not driven by the number of galaxies in each mass bin.) This is in contrast to the strong correlation found between mass and star formation in the past by Heavens et al. (2004) and Panter et al. (2007). We conclude, then, that the observed correlation between spin chirality and early star formation is not driven by mass but by star formation activity.

So far, we have used the galaxies from Galaxy Zoo classified as clean, which limits our sample to only 12 897 galaxies. Because there are many more galaxies in the MOPED catalogue, we have implemented the following algorithm to increase the Galaxy Zoo sample. We weight the chirality of a galaxy by the number of votes from the public. If most people voted for one direction, this algorithm converges to the clean sample we used before. The results of the correlation so obtained are similar to Fig. 1 within the errors bars.

4 DISCUSSION AND CONCLUSIONS

Halo spin directions correlate with the large-scale structure (see, for example, Bailin & Steinmetz 2005; Hahn et al. 2007; Trujillo, Carretero & Patiri 2006). Haloes in sheets tend to have their angular momentum parallel to the sheet; a weaker indication is observed for haloes in filaments, which have their spin perpendicular to the filament direction.

Spin directions are also correlated, as seen in observations (Pen et al. 2000; Slosar et al. 2009) and as predicted by tidal-torque theory (Catelan & Porciani 2001; Catelan et al. 2001; Crittenden et al. 2001; Porciani et al. 2002).

We have found a significant correlation between past star formation activity and the degree of coherence of spin chirality for galaxies in a spatial patch (pixel spin chirality). While we have only used the chiral information of nearly face-on galaxies, the detection of a non-zero signal can only be produced if spin orientations are correlated. The correlation is highest for regions in which galaxies have formed most of their stars in the past. We do not find significant correlations with spin coherence for any of the other measured galaxy properties that we have considered (metallicity, stellar mass, metallicity history).

We note that using chiral information rather than the axis inferred from the projected ellipsoid is safer from the perspective of potential systematic effects. The reason for this is that inferred properties of stellar population are likely to be affected by the galaxy being viewed face-on or edge-on. These properties, however, cannot be affected by the galactic arms winding one way or another.

Our analysis indicates that neighbouring spiral galaxies, which have similar star formation histories, also have their spins aligned. We can interpret this as the large-scale environment influencing dark matter halo spins, giving it a large-scale coherence length, and that either halo spin, environment, or a combination of the two, influence galaxy star formation histories. This can be understood in the context of tidal-torque theory. Galaxies that have their spins aligned are formed in the same filament or sheet and at about the same time.

This correlation is stronger for regions comprising galaxies with older stars, while regions containing significant fractions of galaxies with recent star formation exhibit a smaller correlation with spin coherence. This can be understood as these galaxies being formed in the field and thus being affected by a random tidal field and at different epochs or having had a recent major merger. This would promote recent star formation but deviate the spin direction from that set by the cosmological tidal field.

Our results imply that in simulations of galaxy formation we should expect to detect the early formation of large spiral galaxies in the filaments around clusters. It is the haloes in the filaments that should carry the majority of the star formation of the large spirals. Further, we would expect that most star formation today should be in the field, away from the filaments, and that these objects should have randomly oriented spins. This finding indicates that spin and the correlation between spin and star formation are new, measurable quantities that offer a new complementary way to explore and quantify the effect of environment on star formation (Bamford et al. 2009). We are planning to explore these issues using the cosmological simulations of galaxy formation.

Another possible implication for these results involves weak gravitational lensing studies. The potential of a weak lensing survey to yield a faithful reconstruction of the cosmological distribution of dark matter is limited by the unknown intrinsic alignment of galaxy shapes. There is evidence that intrinsic galaxy shapes are spatially correlated (Heavens, Refregier & Heymans 2000b; Pen, Lee & Seljak 2000; Brown et al. 2002), because the alignment of galaxy disc orientations is induced by halo spin correlations (Catelan et al. 2001).

Our results seem to indicate that, if the star formation history could be measured for at least some of the lensed galaxies, the properties of their star formation histories could be used to predict galaxy spin alignment and thus intrinsic shape alignment.

ACKNOWLEDGMENTS

RJ and LV are supported by FP7-PEOPLE-2007-4-3 IRG, FP7-PEOPLE-2007-4-3-IRG n. 202182 and by MICINN (the Spanish Ministry for Science and Innovation) grant AYA2008-03531. RJ and LV thank ICC at UB for hospitality. RJ, AS and LV thank the Galileo Galilei Institute for Theoretical Physics (GGI) in Florence, where part of this work was carried out, and INFN for partial support.

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