Clues on the origin of galactic angular momentum from looking at galaxy pairs

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ABSTRACT

We search for correlations between the spin in pairs of spiral galaxies, to study if the angular momentum gain for each galaxy was the result of tidal torques imprint by the same tidal field. To perform our study we made use of a sample of galaxy pairs identified using the Sloan Digital Sky Survey. We find a weak, but statistically significant correlation between the spin magnitude of neighbouring galaxies, but no clear alignment between their orientation. We show that events such as interactions with close neighbours play an important role in the value of the spin for the final configuration, as we find these interactions tend to reduce the value of the $\lambda$ spin parameter of late-type galaxies considerably, with dependence on the morphology of the neighbour. This implies that the original tidal field for each pair could have been similar, but the redistribution of angular momentum at later stages of evolution is important.

Key words: galaxies: formation – galaxies: fundamental parameters – galaxies: interactions – galaxies: statistics – galaxies: structure – cosmology: observations.

1 INTRODUCTION

A fundamental issue in the study of galaxy formation and evolution is the internal angular momentum, from its acquisition to identifying the role it plays in determining the final structure of galactic systems.

To explain the origin of the internal angular momentum in galaxies, Hoyle (1949) proposed the tidal field theory, later studied by Peebles (1969) and White (1984). In this theory, galaxies acquire their angular momentum by gravitational torquing exerted, in the early Universe, by neighbour protogalaxies. The tidal fields from the large-scale structure surrounding the protogalaxy exert a torquing moment increasing the angular momentum of the system, which grows linearly in time prior to the gravitational collapse of the structure as protogalaxies have large linear sizes, and thus, the surrounding material is able to imprint angular momentum efficiently. At later stages, after the protogalaxy decouples from the expanding background and turns around, the growth of angular momentum is reduced to a second order effect, because the collapse dramatically reduces the lever arms (Schaefer 2009).

Several analytical and numerical studies have been performed to study this theory. The first concern was to quantify the amount of angular momentum imprinted on the galaxies (Peebles 1969; Doroshkevich 1970; White 1984; Barnes & Efstathiou 1987). It is usual to express the total angular momentum of the galaxies through the dimensionless angular momentum parameter $\lambda$, which in standard cosmological models peaks at values around $\lambda_0 \approx 0.04$ and shows a log-normal distribution with a spread in the logarithm of $0.48 < \sigma_\lambda < 0.66$ (for a compilation of theoretical estimates on $\lambda_0$ and $\sigma_\lambda$ see Shaw et al. 2006). In consistency with what was found in the indirect studies of Syer, Mao & Mo (1999), the estimates of the distribution of $\lambda$ for cosmological dark matter haloes from analytical calculations and N-body simulations, have recently been shown to be in agreement with inferences of this quantity from observed galactic structural parameters for large volume limited samples, by Hernandez et al. (2007) and Berta et al. (2008).

Since the introduction of the $\lambda$ parameter, and with the boom of high resolution N-body simulations and detailed semi-analytical models, a well stocked collection of studies...
has emerged, some looking at the evolution of the spin parameter (Warren et al. 1992; Bullock et al. 2001; Vitvitska et al. 2002; Pierani, Mohayaee & de Freitas Pacheco 2004, Davis & Natarajan 2009), dependencies with environment (Avila-Reese et al. 2005; Maccio et al. 2007; Bett et al. 2007) and correlations with virial mass (Barnes & Efstathiou 1987; Cole & Lacey 1996; Tonini et al. 2006; Bett et al. 2007, Cervantes-Sodi et al. 2008), and others concerning the direct influence of this parameter on the internal structure of the galaxies (Fall & Efstathiou 1980, Mo, Mao & White 1998, van den Bosch 1998; Jimenez et al. 1998, Prantzos & Boissier 2000, Boissier et al. 2001, Hernandez & Cervantes-Sodi 2006, Berta et al. 2008, Cervantes-Sodi & Hernandez 2009). Most of this works deal only with numerical simulations, lacking observational counterparts. This, as the angular momentum of the dominant dark haloes can not be directly measured in real galaxies, although some recent efforts have begun to address the issue of obtaining large observational samples as counterparts (e.g. Berta et al. 2008; Cervantes-Sodi et al. 2008). The orientation of the angular momentum, however, is easier to obtain, if one assumes that the shape of the galaxies is largely coupled to the overall angular momenta of the haloes.

The interest concerning possible alignments between galaxies due to the mechanism of acquisition of angular momentum, has motivated several observational studies. Gott & Thuan (1978), exploring the angular momentum in the local group, pointed out that if a pair of galaxies (like the Galaxy and M31) is formed in isolation, and the collapse phase of formation was short compared with other dynamical timescales, the spin vectors of the galaxies should be perpendicular to the separation vector between the galaxies and parallel between them. This, for the particular case of the local group, holds rather well. Sharp, Lin & White (1979) extended the study to a sample of nearly 100 pairs and reported a complete lack of correlation between the spins. Oosterloo (1993) reached the same conclusion, contrary to the result obtained by Helou (1984), who found an asymmetric correlation; they report that the spin vectors avoid being parallel, in favour of the anti-parallel configuration. More recently, Pestaña & Cabrera (2004) studied the relative alignment of spin axes for observed pairs of spiral galaxies, and found some significance against the null hypothesis of random orientations of binary spiral galaxies. They conclude that complex and repeated interactions probably occur in binary spiral galaxies, so that spins that are parallel, antiparallel or nearly orthogonal often occur. Slosar et al. (2009) detected a correlation in the spin directions of pairs of spiral galaxies, with significant correlation at small separations (< 0.5 Mpc/h).

With the aim of elucidating the process of galaxy assembly, some studies concerning alignments of galaxies in clusters have also been performed. It is believed that galaxies and clusters are formed through a process of hierarchical accretion. In that case, primordial alignments could quickly be erased by dynamical interactions (Cottts 1996; Plionis et al. 2003), and the current alignments could be produced by recent accretion episodes (Faltenbacher et al. 2005). The positive detection of alignments seems to depend on several characteristics of the clusters, such as the presence of substructure (Plionis & Basilakos 2002), its accretion history (Faltenbacher et al. 2005), the morphology of the galaxies (Faltenbacher et al. 2007; Torlina, De Propris & West 2007; Wang et al. 2009) and the morphology of the cluster itself (Aryal & Saurer 2006; Aryal, Paudel & Saurer 2007), which reflects not only the initial conditions, but the dynamical interactions taking place in such complex systems.

Using numerical simulations, Barnes & Efstathiou (1987) fixed their attention on this issue, and found no consistent indication of coherence in the spins of adjacent objects. The result of Bailin & Steinmetz (2005) is similar, they could not find a clear tendency for the principal axes of neighbouring haloes to point in a preferred direction, and Porciani, Dekel & Hoffman (2002) argue that spatial correlation of spins on scales larger than a few Mpc, induced by primordial tidal torques, are strongly affected by non-linear effects.

In this paper we extend the study of angular momentum correlations between neighbouring galaxies, using the λ parameter to account for the magnitude of the spin of observed galaxies. This adds an extra variable to the analysis of angular momentum in observed galaxy pairs, which had up to now been limited to considering only the orientation of the galaxies. A more quantitative description of the problem is hence possible, allowing for a more detailed comparison to the outcome of cosmological simulations, and yielding interesting constraints on the origin of spiral galaxy pairs. As a first test we begin with the simplest case, that of galaxy pairs. This is a regime which makes our work complementary to existing studies in clusters e.g. Faltenbacher et al. (2005) or Wang et al. (2009). Extensive studies on the effects of the large-scale environment and interactions with neighbouring galaxies on various other galaxy properties are presented by Park, Gott & Choi (2008, hereafter PGC) and Park & Choi (2009).

The plan of this paper is as follows. In Section 2, we review the derivation of the λ spin parameter for inferred haloes of spiral galaxies as developed in Hernandez & Cervantes-Sodi (2006), in Section 3 we present the SDSS sample of galaxy pairs used in the present work. Section 4 presents the results from the analysis, and finally, in Section 5, we summarize our general conclusions.

2 ESTIMATION OF THE SPIN FROM OBSERVABLE PARAMETERS

To quantify the magnitude of the angular momentum, we employ the λ spin parameter as introduced by Peebles (1969);

$$\lambda = \frac{L}{GM^{3/2}}$$

where $E$, $M$ and $L$ are the total energy, mass and angular momentum of the configuration, respectively. In Hernandez & Cervantes-Sodi (2006) we derived a simple estimate of total λ for dark halos hosting disc galaxies in terms of observational parameters, and showed some clear correlations between this parameter and structural parameters, such as the disc to bulge ratio, the scale height and the colour. Here we recall briefly the main ingredients of this model. The model considers only two components for galaxies, a disc for the baryonic component with an exponential surface mass density $\Sigma(r)$;
\[ \Sigma(r) = \Sigma_0 e^{-r/R_d}, \]  
\[ \rho(r) = \frac{1}{4\pi G} \left( \frac{V_d}{r} \right)^2. \]  

where \( r \) is a radial coordinate and \( \Sigma_0 \) and \( R_d \) are two constants which are allowed to vary from galaxy to galaxy, and a dark matter halo having an isothermal density profile \( \rho(r) \), responsible for establishing a rigorously flat rotation curve \( V_d \) throughout the entire galaxy; 

\[ \lambda = \frac{2^{1/2}V_d^4 R_d}{G M_H}. \]  

Finally, we introduce a baryonic disc Tully-Fisher (TF) relation: \( M_d = C_{TF} V_d^{3.5} \), and taking the Milky Way as a representative example, we evaluate \( F \) and \( C_{TF} \) to obtain 

\[ \lambda = 21.8 \left( \frac{R_d}{h \text{kpc}} \right) \left( \frac{V_d}{h \text{km} \text{s}^{-1}} \right)^{1/2}. \]  

In Cervantes-Sodi et al. (2008) we tested the accuracy of our estimate of \( \lambda \), comparing the value obtained using equation 4 to the actual value of \( \lambda \) from numerically simulated galaxies from six distinct groups, where the actual value of \( \lambda \) is known and where we had also estimated it through equation 4 as baryonic disc scale lengths and disc rotation velocities for the resulting simulated galaxies were given. The test showed an unbiased and tight one-to-one correlation, with very small dispersion leading to errors < 30%. Application to a large volume limited sample of over 11,000 galaxies from the SDSS yielded a log-normal distribution of \( \lambda \) for the total sample, interestingly in consistence with results from cosmological n-body simulations, presented in Hernandez et al. (2007). The above results were then reproduced by Berta et al. (2008), using a larger sample of 50,000 galaxies also from the SDSS, and a refined version of the \( \lambda \) estimate given here, for spiral galaxies. 

3 THE SDSS SAMPLE 

The sample of galaxy pairs used in this work comes form a study by Park, Gott & Choi (2008, hereafter PGC), using data from the SDSS. It is a volume-limited sample of galaxies with absolute magnitude \( M_r < -19.5 + 5 \log h \) in the redshift interval 0.001 < \( z < 0.5 \). Since most theoretical studies concerning spin distributions present their results at \( z = 0 \), we limited the sample to low redshifts. 

The nearest neighbour for a given galaxy is found requiring the following conditions; (1) the neighbour galaxy can not be fainter than the target galaxy by more than \( \Delta M_r \), (2) it must have the smallest projected separation across the line of sight from the target galaxy and (3), it must present a radial velocity difference less than \( V_{\text{max}} \). We choose \( \Delta M_r = 0.5 \) to include only influential neighbours and not merely satellite galaxies. In PGC it was shown that the selection of target galaxies having neighbours fainter by more than \( 0.5 \) mag produces similar results but drastically reduces the number of target galaxies as their absolute magnitude cut becomes brighter, which reduces the statistical significance of the results. 

To determine \( V_{\text{max}} \), PGC searched for all neighbours with a velocity difference of < 1000 km s\(^{-1}\) with respect to each target galaxy and with a magnitude not fainter by more than \( \Delta M_r \). When looking at the rms velocity difference of the neighbours as a function of the projected separation, this remains constant out to 50 h\(^{-1}\) kpc, at 255 and 169 km s\(^{-1}\) for early and late type target galaxies respectively. In this way, we adopt \( V_{\text{max}} = 600 \) and 400 km s\(^{-1}\) for early and late type galaxies, limits that correspond to about 2.3 times the rms values. 

Given that the limiting magnitude of the sample is \( M_r = -19.0 + 5 \log h \), we study only those target galaxies brighter than \( M_r = -19.5 + 5 \log h \), in order to avoid losing neighbours, we fixed our attention on pairs of relatively bright galaxies. For more details of the sample see Park, et al. (2008). For the same sample, Choi et al. (2007) have determined the exponential disc scale, absolute magnitude, velocity dispersion, de Vaucouleurs radius and eccentricity for each galaxy, assuming a \( \Lambda \text{CDM} \) universe with \( \Omega_M = 0.27 \), \( \Omega_{\Lambda} = 0.73 \) and \( h = 0.71 \). 

In order to discriminate between elliptical and disc galaxies, we used the prescription of Park & Choi (2005) in which early (ellipticals and lenticulars) and late (spirals) types are segregated in a \( u - r \) colour versus \( g - i \) colour gradient space and in the concentration index space. They tested extensively the selection criteria through direct comparison of visually assigned types for a large sample of several thousand galaxies. The specific selection criteria can be found in Park & Choi (2005), but essentially select as early types, galaxies with red colours, minimal colour gradients and high concentration indices. Throughout the paper we will consider ellipticals and lenticulars as early type galaxies, and spirals as late type ones. 

In the next section we will examine the correlation between the angular momenta of galaxies in pairs, taking into account angular momentum magnitude through the \( \lambda \) spin parameter, and direction through position angle. Later we will investigate if the angular momentum of a given galaxy is modified by the presence of a neighbour. To conduct these inquiries, we obtained four different subsamples according to the following criteria. 

Our sample A, used to search for a correlation in the \( \lambda \) value of spiral galaxy pairs, contains 347 pairs of late type - late type galaxies, with 0.001 < \( z < 0.5 \), limiting magnitude of \( M_r = -19.5 + 5 \log h \), and \( R_d \) measured by Choi et al. (2007), and rotational velocities inferred from the absolute magnitude introducing a TF relation (Pizagno et al. 2007), which is all the information needed to calculate \( \lambda \) from equation 4. To avoid the problem of internal absorption in edge-on galaxies (Unterborn & Ryden 2008; Cho & Park 2009), and consequently underestimating rotational velocities, we limit the sample to spiral galaxies having axis ratios \( b/a > 0.6 \).
To study the correlation of the angular momentum direction between members of a spiral pair, we constructed sample B, composed of 218 pairs, with the same redshift range and limiting absolute magnitude as sample A. Supposing the position angle of observed galaxies to be perpendicular to their angular momentum vector, we have an indicator of the angular momentum orientation, albeit with a degeneracy between parallel and anti parallel spins. Given the difficulty of measuring the position angle for face-on late-type galaxies, we used pairs of spiral galaxies with $b/a < 0.7$. This is the reason why we could not use the same sample A to search for a correlation in the direction of the angular momentum.

In both samples, A and B, we required that the nearest neighbour of a given neighbour galaxy in a galaxy pair, should be the target galaxy itself, in this way we search for spin correlations for pairs involving only two galaxies, the simplest scenario. To test the response of the spin to the presence of a companion, we relaxed both this condition and the condition of the neighbour galaxy being a late type galaxy, which increases the number of galaxy pairs to 3624 for sample C, which will be used to measure the response of the value of $\lambda$ to the distance of the nearest neighbour, and to 2037 for sample D with the position angle well determined for every galaxy involved, to determine the influence of a neighbour on alignment.

When studying the influence of a nearby galaxy on the value of the spin, the distance between galaxies is normalized to the virial radius of the neighbour. We define the virial radius of a galaxy as the projected radius where the mean mass density within the sphere of radius $r_{\text{vir}}$ is 200 times the critical density or 740 times the mean density of the universe.

$$r_{\text{vir}}^3 = \left( \frac{3}{4\pi} \right) \left( \frac{200 \gamma L}{\rho_c} \right),$$

with the relative mass-to-light ratios for early type galaxies (ellipticals and lenticulars) twice the same ratio for the late types (spirals), $\gamma(\text{early}) = 2 \gamma(\text{late})$, following Choi et al. (2007), who report that the central velocity dispersion of early type galaxies brighter than $M_r = -19.5$, is about $\sqrt{2}$ times that of late types. Since we adopt $\Omega_M = 0.27$, we have $200\rho_c = 200\Omega_M / H_0 = 740\Omega_M$, which is almost equal to the virialized density $\rho_{\text{crit}} = 18\pi^2 / \Omega_M (H_0 h)^2 = 760\Omega_M$, in the case of a LCDM universe (Gott & Rees 1975). Finally, we introduced the mean value for the density of the Universe, $\bar{\rho} = (0.0223 \pm 0.0005)(\gamma L)_{-20}(h^{-1}\text{Mpc})^{-3}$, where $(\gamma L)_{-20}$ is the mass of a late type galaxy with $M_r = -20$ (Park et al. 2008). In this way, the virial radii of galaxies with $M_r = -19.5$, -20.0 and -20.5 are 260, 300 and $350 h^{-1}$ kpc for early types and 210, 240 and 280$h^{-1}$ kpc for late types, respectively.

Having limited ourselves to such relatively massive systems, which exclude any dwarf galaxies, also gives confidence on the validity of the constant baryon fraction hypothesis used in the estimates of $\lambda$. The above, as small systems where substantial mass loss due to the feedback effects of star formation probably applies, are not included.

\section{Results}

The stringent selection criteria described above ensure that our samples contain only galaxies where our estimates of the spin are most reliable, although the samples are reduced to a small fraction of the total SDSS field, they remain statistically significant.

The results of our $\lambda$ estimates and position angle studies appear in this section. Section 4.1 tests the angular momentum acquisition mechanism through an exploration of the correlations in magnitude and orientation of the angular momentum for close pairs of spiral galaxies. In section 4.2 we investigate the effect on spin magnitude and orientation, of the interaction of a spiral galaxy with another galaxy, as a function of the separation between them, regardless of the morphology of the companion.

\subsection{Spin correlations}

It is reasonable to think that, given the proximity of the galaxies in each pair, both galaxies are immersed in the same tidal field. The amount of angular momentum gained by each galaxy should be similar, proportional to the tidal torques exerted by the surrounding material and inversely proportional to the mass of each galaxy. This assumes that the two components of the present pair have been in close association, at least since the phase of angular momentum acquisition. We explore this hypothesis with the selected sample of pairs of spiral galaxies, calculating spin parameters using equation \[5\] and the total mass from the baryonic Tully-Fisher relation introduced to obtain equation \[8\].

If both member galaxies of a pair were exposed to the influence of the same tidal field, their product $\lambda M$ should show a clear and tight 1 to 1 correlation. In Fig. 1 top panel is shown the spin mass product of nearest neighbour galaxies $M_2 \lambda_2$, as a function of the same product for target galaxies $M_1 \lambda_1$, in units of solar masses for the 347 pairs of late type - late type galaxies extracted from our sample A. In the scenario where both galaxies gained their angular momentum through interactions with a constant tidal field, we should see a clear correlation, but the correlation between the products for neighbouring galaxies in this case is low, with a correlation index of $r^2 = 0.247$.

To quantify the low level correlation seen in the top panel of figure 1, we produced a large number of equivalent mock catalogues of spiral-spiral galaxy pairs through Monte Carlo simulations. Each, with a total of 347 pairs, was obtained through sampling a fixed distribution function for both of the numbers which describe the members of an observed pair. A random value of $M$ and $\lambda$ is picked for each member of a sampled pair, until one obtains as many mock pairs as present in our sample A.

Given the restriction in the absolute magnitude imposed when selecting the observed pairs, the first condition to find the nearest neighbour, a constraint is imposed upon the difference in mass within the members of a given pair. The mass input for the test was chosen observing this restriction, using a constant density distribution with upper and lower limits for the mass as imposed on the SDSS pairs sample. The values of $\lambda$ were taken from the log-normal distribution obtained empirically in Hernandez et al. (2007) with parameters $\lambda_0 = 0.0394$ and $\sigma_\lambda = 0.509$, for a larger sample
by a normal distribution with a spread of 0.063, it places the correlation between the SDSS pairs about 1.9σ above the expected for null intrinsic correlation between \( \lambda_1 M_1 \) and \( \lambda_2 M_2 \). Even though the correlation for the sample of SDSS galaxy pairs seems weak and the correlation index is low, the correlation is significantly stronger than that obtained for null intrinsic correlation mock samples. We must take into account that the correlation extends over 1.5 magnitudes in the \( M \lambda \) product, and that this relation is dominated by galaxy pairs with large separations.

Due to the restriction in magnitude imposed when defining the sample of observed pairs, the difference in mass between each member of a pair is small, and allows us to search for a direct correlation between \( \lambda_1 \) and \( \lambda_2 \). The result, using the same sample A, shows no difference with the previous test, with \( r^2 = 0.202 \), a weaker value but still larger than what is obtained with the results of a Monte Carlo test with no intrinsic correlation at all; with \( r^2 = 0.0056 \) and \( \sigma = 0.0604 \). It appears likely that the correlations shown in Table 1 have their origin in a common tidal field having at least partly responsible for imprinting the angular momentum to both members of the pairs studied. However, the fact that this correlations are weak, points to other angular momentum acquisition and modification mechanisms having being at work, e.g. mergers.

So far we have centred our attention on the magnitude of the spin parameter, but we have not yet examined the direction of the angular momenta in the pairs.

For the analysis of the angular momentum direction, we use sample B. We measured the difference in the position angle for the galaxies of each pair, restricted to vary in the range \( 0 < \Theta < 90 \), given our impossibility to discriminate between parallel and anti-parallel spins. Once obtaining \( \Theta \) for each pair, following the method proposed by Yang et al. (2006), we count the total number of pairs, \( N(\Theta) \), for a number of bins in \( \Theta \). Next, we construct 100 random samples in which we randomized the orientation of the galaxies, respecting the selection criteria of the real sample, and we computed the average number of pairs \( \langle N_R(\Theta) \rangle \), as a function of \( \Theta \). By construction, the random samples have the same selection effects as the real sample of pairs, so any significant difference between \( N(\Theta) \) and \( N_R(\Theta) \) reflects a genuine alignment between galaxy pairs.

To quantify the strength of any possible alignment, we define the normalized pair count as

\[
N_p(\Theta) = \frac{N(\Theta)}{\langle N_R(\Theta) \rangle}.
\]

For a complete absence of alignment we should obtain \( N_p(\Theta) = 1 \). To assess the significance of the deviation of the normalized pair count form unity, we use \( \sigma_R(\Theta) / \langle N_R(\Theta) \rangle \), where \( \sigma_R(\Theta) \) is the standard deviation of \( N_R(\Theta) \) obtained form the 100 random samples.

The result of applying this technique to our sample B is

![Figure 1](image_url). \( \lambda_1 M_1 \) of target galaxies against \( \lambda_2 M_2 \) of nearest neighbour galaxies, in units of solar masses, for 347 pairs. **Top panel:** Pairs of sample A with a \( r^2 = 0.247 \). **Bottom panel:** for comparison, result from a Monte Carlo sample with no inherent correlation beyond what is imposed by the magnitude selection criteria in the observed sample, with \( r^2 = 0.045 \).

![Table 1](image_url). Correlation indexes for Sample A galaxies and mock catalogues, showing for the latter \( \langle r^2 \rangle \pm \sigma \) values.

| \( r^2 \)       | Sample A | mock catalogues |
|-----------------|----------|-----------------|
| \( M_2 \lambda_2 \) vs \( M_1 \lambda_1 \) | 0.247    | \( 0.129 \pm 0.063 \) |
| \( \lambda_2 \) vs \( \lambda_1 \)       | 0.202    | \( 0.0056 \pm 0.0604 \) |
The low correlation between the spin of neighbouring galaxies can be explained by the early acquisition of angular momentum through primordial torques exerted by the surrounding tidal field on the pair (Barnes & Efstathiou 1987; Navarro, Abadi & Steinmetz 2004), which induces an initial tidal field on the pair (Barnes & Efstathiou 1987; Saurer 2003; Pierani et al. 2004) and minor mergers (Gardner 2001; D’Onghia & Navarro 2006) are to then blur the initial correlations, to the point where no evident alignment correlation remains, highlighting the effect of later processes. In the next subsection we will focus on the effect of interactions in the evolution of the spin.

4.2 Interacting galaxies

In this subsection we investigate if there is a response to the interaction between neighbouring galaxies in the $\lambda$ spin parameter, as a function of the separation distance between the members of the observed pairs. In this case we are only concerned with the value of $\lambda$ for late type target galaxies, irrespective of the $\lambda$ characteristics of the nearest neighbour. This allowed us to increment the number of systems studied, through the inclusion of spiral target galaxies having early type closest neighbours, for the third of our tests.

Recently Park & Choi (2009) reported a dependence of the absolute magnitude of the target galaxy on the nearest neighbour separation, where the galaxy luminosity in the red decreases as the separation distance decrease. Given that in the calculation of $\lambda$ we use $M_r$ to assign a $V_\lambda$ value for equation $\lambda$, we limited the sample to galaxies having magnitudes in the range $-19.5 < M_r < -20.5$, to focus our study on the response of $\lambda$ not merely as a consequence of the dependence found by Park & Choi (2009) on magnitude, but as a directly consequence of the influence of a neighbour galaxy on the value of $\lambda$. Taking only a narrow range in $M_r$ limits the effect on the estimates of $\lambda$ of a correlation between $M_r$ and the nearest neighbour distance, to better isolate and assess the effects of the distance to the nearest neighbour, on the spin of the target galaxy.

The top panel of figure 3 shows $\lambda$ values of the 3624 target late type galaxies of sample C, as a function of the distance to their closest neighbours, normalized to the virial radius of the neighbour galaxy, calculated using equation $\lambda$. The sample is divided into 7 bins, where the median $\lambda$ values are shown with their dispersion presented as thin error bars and the uncertainty represented by thick error bars; this convention will be followed for the next figures. For separations larger than the virial radius of the neighbour galaxy, the mean value of $\lambda$ appears constant, but as soon as the distance becomes smaller than $R_{\text{vir}}$, the median value of $\lambda$ starts to decrease, a clear indication of the interaction. Galaxy harassment and various angular momentum loss mechanisms, such as dynamical friction (Hernquist 1993), might begin to operate during the interaction, even at large distances, as the galaxies first cross into their virial radii (PGC; Park & Choi 2009).

In going to the first bin, a substantial increase in the dispersion of the inferred values of $\lambda$ is evident. However, for such small separations, systems within 0.02 of their virial radius, a strong interaction is ongoing. This implies the systems are heavily disturbed and strongly out of equilibrium; see e.g. the numerical simulations of galaxy collisions of Hernandez & Lee (2004), where fluctuations in potential and kinetic energies of the total system are assessed as a function of the pair separation. This invalidates the assumptions going into the simple formula used to estimate $\lambda$, making the values of this quantity in the first bin of figure 3, top panel, useful only as indications of strong interactions at small distances, and not as indicative of total halo $\lambda$.

The complementary study using the difference in the position angle $\Theta$, to account for the relative orientation of the galaxies within a pair, is shown in Fig. 3 bottom panel using sample D, where $\Theta$ is plotted against the separation distance between neighbouring galaxies, normalised by the virial radius $R_{\text{vir}}$ of the neighbour galaxy. The sample is divided into 7 bins, where the median $\Theta$ values are shown with their dispersion presented as thin black error bars, as in the preceding plot. If the orientations of the galaxies between neighbours were isotropic, we would expect a median

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**Figure 2.** Normalized probability distribution of the difference in the position angle, $\Theta$, for the pairs in sample B, dotted line representing $f_{\text{pairs}} = 1$, and the error bars give the value of $\sigma_R(\Theta) / \langle N_R(\Theta) \rangle$. 

| $\Theta$ | Probability |
|---------|-------------|
| 0       | 0.4         |
| 10      | 0.6         |
| 20      | 1.2         |
| 30      | 1.6         |

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| $M_r$ | $\lambda$ |
|-------|-----------|
| -19.5 | 0.4       |
| -20.5 | 0.6       |
Figure 3. Top panel: $\lambda$ value for the 3624 target late type from sample C as a function of the separation distance to their nearest neighbour, normalized by the virial radius of the neighbour galaxy, $R_{\text{vir}}$. Bottom panel: Difference in the position angle $\Theta$ for the 2037 late type pairs from sample D as a function of their normalized separation distance $d/R_{\text{vir}}$.

$\Theta$ value of 45, showed as a broken line in the plot. As can be seen, the median value of $\Theta$ decreases as the separation distance decreases below the virial radius of the neighbour galaxy, meaning that the galaxies tend to be aligned (or anti-aligned) as their neighbours get closer to them.

Summarising, we have shown that the angular momentum of spiral galaxies, not only in its orientation but also in its magnitude, is affected by the presence of a companion, once the galaxies are within the virial radius of their neighbour. Once galaxies cross into their virial radii, a slight but measurable decrease in $\lambda$ begins to operate. A corresponding increase in alignment also appears, but only in going to very close systems where the out-of-equilibrium situation makes determining values of $\lambda$ unfeasible.

In a previous work (Cervantes-Sodi & Hernandez 2009) using a reduced sample of very well studied spiral galaxies, two of us showed how the star formation rate has a marked dependence on $\lambda$, it decreases when the value of $\lambda$ increases. If such tendency remains in perturbed systems, it could explain the enhanced star formation present in interacting galaxies, as due to the decrease of the spin. Some studies (Lambas, Tissera, Alonso & Coldwell 2003; Ellison, Patton, Simard & McConnachie 2008) based on observational samples coming from large galaxy surveys, even show a gradual increase of the star formation as the distance between the interacting galaxies decreases, result completely compatible with our finding of the decrease of the value of $\lambda$ in such circumstances. More recently, Park & Choi (2009), studying the effects of galaxy interactions on galaxy properties, reported the enhancement of the star formation activity for target galaxies within the virial radius of the neighbour galaxy, when this neighbour is a late type galaxy.

We explore the effects of the galaxy type of the nearest neighbour by splitting sample C in two according to the neighbours morphology, and plotting the value of $\lambda$ as a function of the normalised distance between neighbouring galaxies $d/R_{\text{vir}}$, in Fig. 4 left panels. The top panel shows the behaviour when the nearest neighbour is a late type galaxy (2073 galaxies) and bottom panel when it is an early type one (1551 galaxies). The complementary plots showing the difference in the position angle splitting sample D in two according to the neighbours morphology, are shown in the right panels of Fig. 4; top panel for nearest neighbours being late type (1325 galaxies) and bottom being early type (712 galaxies). If we look at the case when the neighbour is a late type galaxy, we see that within the errors, no effects are apparent when the normalised distance is larger than 1, with a slight decrease in the values of $\lambda$ as the normalised distance drops below $1R_{\text{vir}}$ and with an increase in the alignment or anti-alignment between their position angles. The case when the neighbour galaxy is an early type one is more erratic and the trend less evident, in both the magnitude of $\lambda$ and the spin alignment. It is interesting to note that for the first bin, where the interaction is ongoing, we see much more significant disturbances in the value of $\lambda$, when both galaxies are spiral, probably due to the strong hydrodynamical effects of the interaction of two gaseous disks, which are absent when one of the two systems is of early type.

As an extension to the work presented here, it would be desirable to probe particularly high density environments, to test how the situation tends to the picture seen at cluster scales (see Park & Hwang 2009 for environmental effects on cluster galaxies). Within the hierarchical picture of structure formation, evolutionary timescales decrease with increasing ambient densities, which in turn also increase with time. In this way, one could hope to recover an evolutionary sequence for any given process, from a comparative study at zero redshift, extending over a large ambient density range. Also, a fuller 3D alignment study might yield more extensive information. One must be cautious, e.g., on cluster scales, results of 2D alignment studies are sometimes modified when more extensive 3D analysis are performed.

5 CONCLUSIONS

Using pairs of spiral galaxies of comparable size, we searched for correlations between their spins. Using the spin param-
Figure 4. Left panels: $\lambda$ value of target late type galaxies from sample C as a function of the normalized separation distance to their nearest neighbour, $d/R_{\text{vir}}$; top panel: nearest neighbour being a late type galaxy, bottom panel: nearest neighbour being an early type galaxy.

Right panels: difference in the position angle for galaxies from sample D as a function of the normalized separation distance to the nearest neighbour; top panel: nearest neighbour being a late type galaxy, bottom panel: nearest neighbour being an early type galaxy.

eter $\lambda$ to account for the magnitude of the angular momentum, and the position angle for its direction, we found a weak but statistically relevant correlation between the spin magnitude of neighbouring galaxies, but where unable to detect any tendency for alignment.

If we adopt the simplest version of the tidal torque theory to explain the acquisition of angular momentum, we would expect a strong correlation for the spins of spiral galaxies in a pair, if they had formed under the influence of the same tidal field. Our results imply the dominant presence of two complementary effects, the late formation of the galaxy pair, after the epoch of $\lambda$ acquisition was completed, and the blurring of initial conditions due to the clumpy and irregular mass accretion of relatively extended minor merging events.

In going to the trends exhibited by the sample as a function of galaxy separation, we can clearly see the effects of galaxy-galaxy interaction. These appear as soon as the galaxies cross into their virial radii, leading to a gradual decrease in the values of $\lambda$.

Our results do not diminishes the importance of the torquing at early stages of galaxy formation, but give us an insight into the important role of later interactions in the overall evolution of the total angular momentum of the galaxies, as shown by the results obtained from interacting systems, where the spin is visibly perturbed by the presence of a nearby companion.
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