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# The spin of late-type galaxies at redshifts $z \leq 1.2$

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## ABSTRACT

We study the evolution of the galactic spin using data of high-redshift galaxies in the fields of the Great Observatories Origins Deep Survey. Through simple dynamical considerations we estimate the spin for the disc galaxies in our sample and find that its distribution is consistent with that found for nearby galaxies. Defining a dimensionless angular momentum parameter for the disc component of the galaxies ( $\lambda_d$ ), we do not find signs of evolution in the redshift range  $0.4 \leq z \leq 1.2$ . We find that the mass and environmental dependences of the spin of our high-redshift galaxies are similar to those of low- $z$  galaxies, showing a strong dependence on mass, in the sense that low-mass systems present higher  $\lambda_d$  values than high-mass galaxies, with no significant dependence on the environmental density. These results lead us to conclude that although individual disc galaxies might occasionally suffer strong evolution, they evolve in such a way that the overall spin distribution of the galactic population remains constant from  $z \sim 1$  to the present epoch.

**Key words:** galaxies: evolution – galaxies: fundamental parameters – galaxies: general – galaxies: high-redshift – galaxies: statistics – galaxies: structure.

## 1 INTRODUCTION

In the standard picture of galaxy formation, galaxy discs form out of gas that slowly cools out of a hot gaseous halo, conserving its specific angular momentum, and forms a disc at the centre of the potential well of a dark matter halo (White & Rees 1978; Fall & Efstathiou 1980). The specific angular momentum of the pre-collapse gas is generally assumed to be equal to that of the dark matter, which is acquired by tidal torques in the early Universe (Peebles 1969). This simple picture leads to predictions of present-day disc galaxies that show reasonably good agreement with observations (Dalcanton, Spergel & Summers 1997; Avila-Reese, Firmani & Hernandez 1998; Jimenez et al. 1998; Mo, Mao & White 1998; de Jong & Lacey 2000; Pizagno et al. 2005; Dutton et al. 2007); however, later stages of galaxy evolution must certainly include a large variety of processes, such as mergers (Naab, Jesseit & Burkert 2006; Martig et al. 2012), galaxy–galaxy interactions (Cervantes-Sodi, Hernandez & Park 2010; Hwang et al. 2011; Lee et al. 2012) and accretion of cold gas through thin dense filaments (Kereš et al. 2005; Powell, Slyz & Devriendt 2011), that shape the morphology of galaxies.

If this complex scenario is actually taking place, it is remarkable to find the presence of fully formed disc galaxies at high redshift that highly resemble present-day systems (Genzel et al. 2006), requiring only moderate evolution after a rapid early assembly to reproduce the nearby population of Milky Way-type galaxies. Observations of disc galaxies at  $z \leq 1$  show the existence of large discs, suggesting that these kinds of systems must be assembled prior to this epoch (Lilly et al. 1998; Trujillo & Aguerrí 2004; Sargent et al. 2007; Kanwar et al. 2008). Not only do these galaxies have similar sizes to their present-day relatives, but they also follow the same scaling relations with no or only mild evolution. Barden et al. (2005) found weak or no evolution in the stellar mass–size relation for disc-dominated galaxies back to  $z = 1$ . This result is consistent with a passively evolving stellar population at a given mass, with no growth of galaxy discs, or with the idea that in fact the galaxies are growing, but in such a way as to evolve along the same stellar mass–size relation. Recently, results pointing in the same direction were reported by Ichikawa, Kajisawa & Akhlaghi (2012) with a sample extending up to  $z \sim 3$ .

Similar conclusions are reached by studying other relations, such as the Tully–Fisher (TF) relation that evolves, specially for the case of blue bands that are highly sensitive to the recent star formation, but presents only mild or no evolution for near-infrared (NIR) bands (Fernández Lorenzo et al. 2010) and no evolution at all for the case

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of the stellar mass TF relation (Miller et al. 2011). High-redshift galaxies, up to  $z = 3.5$ , do not show evidence of evolution in the Fundamental Plane defined by star formation rate, metallicity and stellar mass (Lara-López et al. 2010). In addition, a roughly constant number density of large disc galaxies since  $z \sim 1$  (Lilly et al. 1998; Sargent et al. 2007) and a mass function that does not present strong features of evolution in the same redshift range (Brichmann & Ellis 2000), all indicate that most of the large disc galaxies have experienced little evolution in the last eight billion years.

Along with mass, angular momentum shapes fundamental properties of galaxies and plays a preponderant role in establishing fundamental relations, such as the TF relation (Koda, Sofue & Wada 2000). In previous studies, we have shown using different samples of galaxies, how the overall morphology of disc galaxies is intimately linked to the galactic angular momentum (Hernandez & Cervantes-Sodi 2006; Cervantes-Sodi & Hernandez 2009; Cervantes-Sodi et al. 2011a), and making use of extended samples from the Sloan Digital Sky Survey (SDSS; Choi, Han & Kim 2010), we have also looked for dependences of the spin parameter on the total mass of the galaxies (Cervantes-Sodi et al. 2008) and on local and global environment (Cervantes-Sodi et al. 2008, 2010, 2011b). The aim of this work is to get empirical distributions of the galactic spin for a sample of high-redshift galaxies, to look for any evolution on the distributions of this parameter and to compare mass and environment dependences of the high-redshift sample with previous results for local galaxies. This paper is organized as follows. Section 2 gives a brief review of our model to estimate the spin for disc galaxies in the sample; the sample details are described in Section 3. In Section 4 we present the general results, with general conclusions appearing in Section 5. Throughout, we adopt  $h = 0.7$  and a flat  $\Lambda$  cold dark matter cosmology with density parameters  $\Omega_{\Lambda,0} = 0.73$  and  $\Omega_{m,0} = 0.27$ .

## 2 ESTIMATION OF THE SPIN FROM OBSERVABLE PARAMETERS

A traditional way to characterize the galactic angular momentum is through the  $\lambda$  spin parameter, as defined by Peebles (1971),

$$\lambda = \frac{L |E|^{1/2}}{GM^{5/2}}, \quad (1)$$

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  $\lambda$  for dark haloes hosting disc galaxies in terms of observational parameters, based on two simple hypotheses: that the specific angular momentum of dark matter and that of baryons are equal, and a constant small baryonic fraction, for systems where the total energy and angular momentum are dominated by the dark matter component. But serious questions arise regarding these hypotheses when studying galaxies at high redshift. Regarding a constant baryonic fraction, a strong dependence on redshift has been suggested (Behroozi, Conroy & Wechsler 2010; Moster et al. 2010; Faucher-Giguère, Kereš & Ma 2011), although no clear consensus has been reached, specially for  $z \geq 1$ . Note, however, that the lack of evolution of the baryonic TF relation argues for little evolution of the baryonic galactic fraction. Concerning the first hypothesis, using high-resolution cosmological simulations, several authors claim that the equality at all times for an evolving galaxy is unrealistic (e.g. Dutton & van den Bosch 2011), but no general consensus has been reached. Recent studies report a large variety of results, some showing a clear one-to-one correlation between the specific angular momentum of baryons and that of

dark matter (Zavala, Okamoto & Frenk 2008), while others present analytic expressions in terms of the dark matter fraction (Sales et al. 2009) or a combination of virial mass and redshift (Kimm et al. 2011) to establish a relation between the angular momentums of both components.

To avoid complications, we must therefore use an angular momentum parameter which focuses on the dynamics of the stellar disc. We retain the quantitative and objective nature of the study, and account for the angular momentum focusing only on the stellar component to define a disc's dimensionless angular momentum parameter  $\lambda_d$  as we did in Cervantes-Sodi et al. (2011b). Here we give a brief account of the model. We consider a disc for the stellar component of the galaxy with an exponential surface mass density  $\Sigma(r)$ ,

$$\Sigma(r) = \Sigma_0 e^{-r/R_d}, \quad (2)$$

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 assume the presence of a dark matter halo responsible for establishing a rigorously flat rotation curve  $V_d$  throughout the disc.

From equation (2), the total disc mass is

$$M_d = 2\pi\Sigma_0 R_d^2. \quad (3)$$

This, combined with our flat rotational curve, leads to an angular momentum of  $L_d = 2V_d R_d M_d$ . Assuming the disc to be a virialized dynamical system, the total energy can be obtained from the total kinetic energy, estimated as arising merely from the dominant rotation. In this case, the kinetic energy of the disc is  $T_d = M_d V_d^2/2$ .

These assumptions allow us to express  $\lambda_d$  as

$$\lambda_d = \frac{L_d |T_d|^{1/2}}{GM_d^{5/2}} = \frac{2^{1/2} V_d^2 R_d}{GM_d}. \quad (4)$$

Finally, we introduce a stellar TF relation (Miller et al. 2011):  $M_d = A_{TF} V_d^{3.869}$  to replace the dependence on  $V_d$  for a dependence on the stellar mass available in our sample (see Section 3) to obtain our final estimation of  $\lambda_d$ .

Note that equation (4) is the same expression we derived in Hernandez & Cervantes-Sodi (2006) to estimate the traditional  $\lambda$  spin parameter for dark matter haloes hosting disc galaxies, divided by the stellar fraction of the galaxy; this is because to obtain the total spin parameter we assumed angular momentum conservation for both components and a constant baryonic fraction, linking the specific angular momentum and the mass of the dark matter to the quantities of the disc component. In our current work, however, we do not attempt to constrain the physical characteristics of the halo but just consider its participation in establishing the flat rotation curve throughout the disc. The parameter  $\lambda_d$  is hence not a  $\lambda$  parameter in the sense of the definition of equation (1), but merely an estimate of a dimensionless angular momentum for a galactic disc, expected to correlate tightly with all type-defining properties.

## 3 GOODS SAMPLE

The sample of high-redshift galaxies used for this study is an updated version of the one presented in Hwang & Park (2009). Here, we give a brief description of the sample, and we refer the readers to Hwang et al. (2011) for a detailed description of the data.

We used a spectroscopic sample of galaxies from the Great Observatories Origins Deep Survey (GOODS), which is a deep multiwavelength survey from NASA's Great Observatories, *Spitzer*, *Hubble* and *Chandra*, ESA's *Herschel* and *XMM-Newton*, and from the most powerful ground-based facilities, with a total observing

area of approximately  $320 \text{ arcmin}^2$  from two carefully selected regions centred on the *Hubble Deep Field-North* (GOODS-N) and *Chandra Deep Field-South* (GOODS-S). From the vast spectroscopic data for GOODS sources in the literature, we used a total number of 6958 galaxies whose spectroscopic redshifts are reliable over the whole fields of GOODS-N (Cohen et al. 2000; Cowie et al. 2004; Wirth et al. 2004; Reddy et al. 2006; Barger, Cowie & Wang 2008; Cooper et al. 2011a) and GOODS-S (Le Fèvre et al. 2004; Szokoly et al. 2004; Mignoli et al. 2005; Vanzella et al. 2005, 2006, 2008; Ravikumar et al. 2007; Kurk et al. 2009; Popesso et al. 2009; Balestra et al. 2010; Silverman et al. 2010; Cooper et al. 2011b; Xia et al. 2011), respectively, with a typical error of  $4 \times 10^{-4}$ . In our analysis, a volume-limited sample with  $M_r \leq -20.0$  and  $0.4 \leq z \leq 1.2$  was used. The rest-frame  $r$ -band absolute magnitude  $M_r$  of galaxies was computed based on the ACS plus NIR photometry with  $K$ -corrections (Blanton & Roweis 2007). The  $1.1(z - 0.1)$  term was added to  $M_r$  for the evolution correction (Wolf et al. 2003). Stellar masses were computed from the  $U$  band to IRAC  $4.5 \mu\text{m}$  photometric data using  $z$ -PEG (Le Borgne & Rocca-Volmerange 2002). The templates used for the stellar mass estimates were determined from PÉGASE.2 (Fioc & Rocca-Volmerange 1999) assuming a Salpeter initial mass function (Salpeter 1955). The templates were produced using different scenarios for the star formation history (see Le Borgne & Rocca-Volmerange 2002) varying the star formation efficiency and infall time-scales, ranging from a pure starburst to a continuous star formation rate, lasting from 1 Myr to 13 Gyr with the requirement for the templates to be younger than the age of the Universe at any redshift. The models include dust computed from PÉGASE.2, consistent with the star formation histories. The typical amount of reddening by dust is within the range  $0.0 \leq E(B - V) \leq 0.15$ . The maximum error associated with the stellar mass estimate is 0.3 dex (see Elbaz et al. 2011 for more details).

This estimate of stellar mass is the one used to infer  $V_d$  needed in equation (4) to calculate  $\lambda_d$ . Choosing a stellar TF relation has a major advantage over traditional TF relations based on specific bands. As recently reported by several authors (Kassin et al. 2007, Fernández Lorenzo et al. 2010, Miller et al. 2011), the stellar TF relation does not seem to evolve with redshift, at least up to redshift  $z \sim 1.7$  (Miller et al. 2012), and presents the smallest scatter among other TF relations, with an intrinsic scatter of 0.058 dex, which is comparable to that seen in local TF relations (i.e.  $\sim 0.049$  in Pizagno et al. 2005).

Given that our spin estimate is suitable only for disc galaxies, we need to segregate the galaxies in our sample according to their morphology. To do that, we adopt the segregation criteria by Hwang & Park (2009) and Hwang et al. (2011), where galaxies are classified into early (E/S0) and late (S/Irr) types by visual inspection. Early-type galaxies are those with little fluctuation in the surface brightness and colour and with good symmetry, while late-type galaxies show internal structures and/or colour variations in the pseudo-colour images. For late-type galaxies we use as a proxy for the scale length  $R_d = R_c/1.68$ , where  $R_c$  is the half-light radius in the  $z$ -band.

In Section 4 we will study the dependence of the spin on the environment. To account for the large-scale environment, we consider a surface galaxy number density estimated from the five nearest-neighbour galaxies ( $\Sigma_5$ ), defined by

$$\Sigma_5 = 5 \left( \pi D_{p,5}^2 \right)^{-1}, \quad (5)$$

where  $D_{p,5}$  is the projected proper distance to the fifth nearest neighbour, which is identified among the neighbour galaxies with

$M_r \leq -19.5$  that have velocities relative to the target galaxy less than  $1000 \text{ km s}^{-1}$ , so as to exclude foreground and background galaxies.

We will also consider the distance to the nearest-neighbour galaxy as a small-scale environmental parameter. The nearest-neighbour galaxy of a target galaxy with absolute magnitude  $M_r$  is the one with the smallest projected separation distance on the sky to the galaxy, is brighter than  $M_r + \Delta M_r$  among those in the sample, with  $\Delta M_r = 0.5$ , and has relative velocity with respect to the target galaxy less than  $\Delta v = |v_{\text{neighbours}} - v_{\text{target}}| = 660 \text{ km s}^{-1}$  for early-type target galaxies and less than  $\Delta v = 440 \text{ km s}^{-1}$  for late-type target galaxies. These velocity difference limits are 10 per cent larger than those we have used for SDSS galaxies in previous studies, i.e. fig. 1 of Park, Gott & Choi (2008), because of the larger redshift uncertainties for GOODS galaxies as compared with SDSS galaxies.

The virial radius of a galaxy within which the mean mass density is 200 times the critical density of the universe ( $\rho_c$ ) is calculated by

$$r_{\text{vir}} = (3\gamma L/4\pi)^{1/3} (200\rho_c)^{-1/3}, \quad (6)$$

where  $L$  is the galaxy luminosity and  $\gamma$  is the mass-to-light ratio. Here, the mass associated with a galaxy plus dark halo system is assumed to be proportional to the  $r$ -band luminosity of the galaxy. We assume that the mass-to-light ratio of early-type galaxies is on average twice as large as that of late-type galaxies at the same absolute magnitude  $M_r$ , which means  $\gamma(\text{early}) = 2\gamma(\text{late})$  following Choi, Park & Vogeley (2007) for SDSS galaxies and Hwang & Park (2009) for GOODS galaxies. The critical density of the universe  $\rho_c$  is a function of redshift  $z$  [i.e.  $\rho_c = 3H^2(z)/(8\pi G)$ ] and  $\Omega_m(z) = \rho_b(z)/\rho_c(z) = \bar{\rho}(1+z)^3/\rho_c(z)$ , where  $\rho_b$  and  $\bar{\rho}$  are the mean matter densities in proper and comoving spaces, respectively. The Hubble parameter at  $z$  is  $H^2(z) = H_0^2[\Omega_{m,0}(1+z)^3 + \Omega_{k,0}(1+z)^2 + \Omega_{\Lambda,0}]$ , where  $\Omega_{m,0}$ ,  $\Omega_{k,0}$  and  $\Omega_{\Lambda,0}$  are the dimensionless density parameters at the present epoch (Peebles 1993). Then, the virial radius of a galaxy at redshift  $z$  in proper space can be rewritten by

$$r_{\text{vir}}(z) = [3\gamma L \Omega_{m,0} / (800\pi\bar{\rho}) / \{\Omega_{m,0}(1+z)^3 + \Omega_{k,0}(1+z)^2 + \Omega_{\Lambda,0}\}]^{1/3}. \quad (7)$$

The mean mass density  $\bar{\rho}$  was computed using the galaxies at  $z = 0.4-1.2$  with various absolute magnitude limits varying from  $M_r = -16$  to  $-20$ . Hwang et al. (2011) found that the mean mass density appears to converge when the magnitude cut is fainter than  $M_r = -17.5$ , which means that the contribution of faint galaxies is not significant because of their small masses. In this calculation, each galaxy is weighted by the inverse of completeness according to its apparent magnitude and colour (see fig. 1 of Hwang & Park 2009). The final values are  $\bar{\rho} = 0.017$  and  $0.013$  ( $\gamma L$ ) $_{-20}$  ( $\text{Mpc}^{-3}$ ) for GOODS-N and GOODS-S, respectively, where  $(\gamma L)_{-20}$  is the mass of a late-type galaxy with  $M_r = -20$ . According to our formula, the virial radii of galaxies with  $M_r = -20$  and  $-21$  are 300 and  $400 h^{-1} \text{ kpc}$  for early types, and 240 and  $320 h^{-1} \text{ kpc}$  for late types, respectively.

The final volume-limited sample contains 827 late-type galaxies with accurate total stellar masses and reliable spectroscopic redshifts.

## 4 RESULTS

Once having segregated the galaxies according to their morphology, and with all the information required to apply equation (4), we obtained the  $\lambda_d$  distribution for all the late-type galaxies in our sample. Usually, as is also the case here, this parameter is well



described by a lognormal function of the form

$$P(\lambda_{d0}, \sigma_{\lambda_d}; \lambda_d) d\lambda_d = \frac{1}{\sigma_{\lambda_d} \sqrt{2\pi}} \exp \left[ -\frac{\ln^2(\lambda_d/\lambda_{d0})}{2\sigma_{\lambda_d}^2} \right] \frac{d\lambda_d}{\lambda_d}. \quad (8)$$

The parameters for the best-fitting distribution are  $\lambda_{d0} = 0.752$  and  $\sigma_{\lambda_d} = 0.499$ . To compare directly with global  $\lambda$  distributions, we need to adopt a recipe to estimate the total angular momentum and mass in terms of stellar parameters. To do so, we first assume that the specific angular momentum of the disc and that of the halo are equal (e.g. Mo et al. 1998; Zavala et al. 2008), and then we need to choose a proper dark matter fraction. As in Hernandez et al. (2007), for a constant dark matter fraction (F1), the  $\lambda$  distribution for the sample of high-redshift galaxies is compatible with results of low-redshift galaxies, with  $\lambda_0 = 0.045$  and  $\sigma_\lambda = 0.499$ . The shape of the distribution strongly depends on the assumed dark matter fraction; just to illustrate this strong dependence we show in Fig. 1 (lower panel) two other distributions – one considering a dependence of the dark matter fraction on the stellar surface density (F2) from Gnedin et al. (2007),

$$F = F_0 \left( \frac{M_* R_d^{-2}}{10^{9.2} M_\odot \text{ kpc}^{-2}} \right)^p, \quad (9)$$

where  $p = 0.2$ , which produces a distribution with  $\lambda_0 = 0.032$  and  $\sigma_\lambda = 0.392$ , and following Faucher-Giguère et al. (2011), one where the mass of the dark matter halo is given in terms of the rotation velocity and redshift,

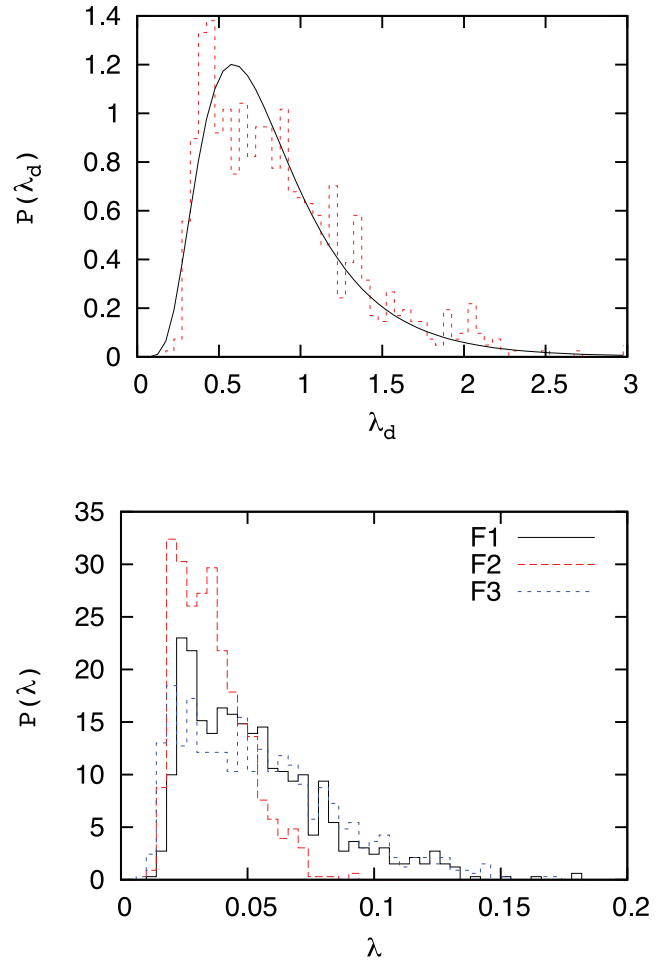
$$M_h = 10^{10} M_\odot \left( \frac{V_d}{50 \text{ km}^{-1}} \right) \left( \frac{1+z}{4} \right) \quad (10)$$

resulting in  $\lambda_0 = 0.046$  and  $\sigma_\lambda = 0.531$ . As shown in Fig. 1 (lower panel), the dependence on the assumed dark matter fraction is strong, with clear changes of the spin distributions according to the dark matter fraction chosen, but giving as a result  $\lambda$  distributions that are consistent with those previously found by different authors, as summarized by Shaw et al. (2006), giving values in the range  $0.03 < \lambda_0 < 0.05$  and  $0.48 < \sigma_\lambda < 0.64$ . To avoid the complication of determining the dark matter fraction, plus the systematic offsets due to the coefficients involved, and the possibility that the specific angular momentum of dark matter and that of stars are not equal (e.g. Kassim et al. 2012), we will present the following results in terms of the disc spin  $\lambda_d$ , which can be interpreted in terms of the global spin selecting a proper dark matter fraction, assuming that the specific angular momentum of dark matter can be traced by that of the baryons.

With our sample extending over a wide redshift range, we search for an evolution with time. Fig. 2 (upper panel) shows  $\lambda_d$  values as a function of redshift, with the sample divided into eight bins, where the median  $\lambda_d$  values are shown with error bars in solid blue lines that represent the  $1\sigma$  confidence intervals based on the bootstrapping resampling method, and error bars in broken black lines denote the dispersion for each bin; this convention will be followed for the next figures. We clearly see that the typical values remain almost constant throughout the whole redshift range.

Bearing in mind that we have chosen a specific TF relation for all the galaxies in our sample, we check if the lack of evolution we find for the disc spin comes directly from the hypothesis of the validity of the same TF relation for the galaxies in the redshift range  $0.4 \leq z \leq 1.2$ . Instead of using one single stellar mass TF relation, we use three different relations of the form

$$\log(M_d) = [a + b \times \log(V_d)] \log(M_0), \quad (11)$$



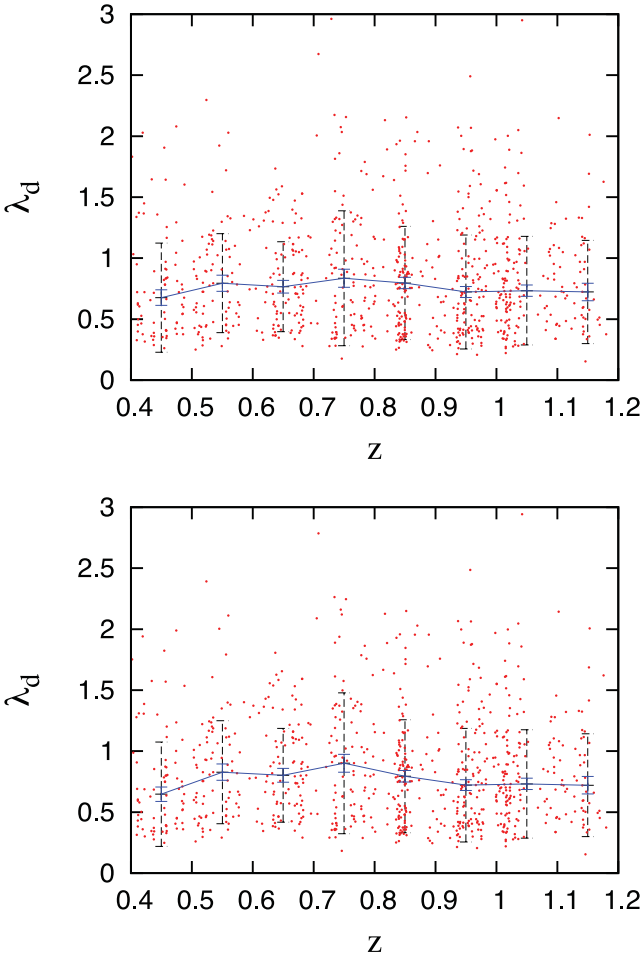
**Figure 1.** Upper panel:  $P(\lambda_d)$  distribution for late-type galaxies in the sample with the best lognormal fit to the data with parameters  $\lambda_{d0} = 0.752$  and  $\sigma_{\lambda_d} = 0.499$ . Lower panel:  $P(\lambda)$  distributions considering three different functions for the dark matter fraction.

where  $M_0 = 10^{10}$  and the constants  $a$  and  $b$ , taken from Miller et al. (2011), are given in Table 1. The result of using a combination of TF relations for the three different redshift ranges is shown in Fig. 2 (lower panel), where we can see that even after using these relations there is no evidence of evolution.

Given the lack of evolution of the  $\lambda_d$  parameter on redshift for the galaxies in our sample, a reasonable test is to check if these galaxies present the same strong dependence of  $\lambda_d$  on mass and a lack of dependence on environment, as presented for low-redshift galaxies (Berta et al. 2008; Cervantes-Sodi et al. 2008, 2010). The upper panel in Fig. 3 shows  $\lambda_d$  as a function of stellar mass, showing a strong dependence, with high-mass galaxies showing typically low  $\lambda_d$  values, as well as lower spread when compared with low-mass galaxies, just the same behaviour as the one showed by low-redshift galaxies (see fig. 5 in Cervantes-Sodi et al. 2008).

For samples of galaxies at low redshift, we previously reported a lack of dependence of the spin parameter on the large-scale environment, which is in good agreement with theoretical expectations (Lemson & Kauffmann 1999); for the present sample of high-redshift galaxies we again recover the same result as shown in Fig. 3 (lower panel).

In Cervantes-Sodi et al. (2010), we found a weak but statistically significant effect of galaxy–galaxy interactions on the  $\lambda$  value of

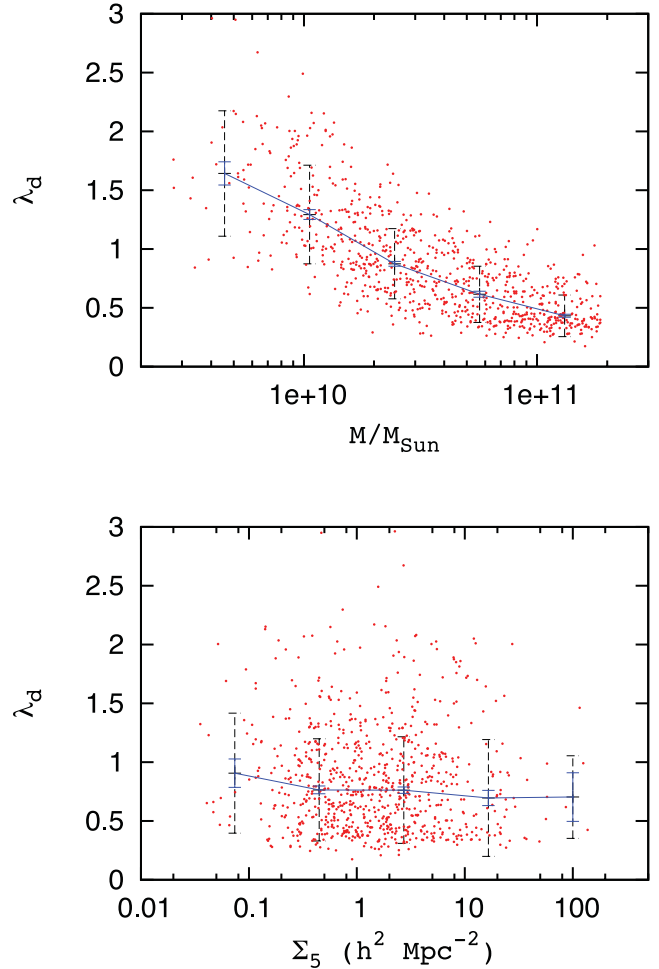


**Figure 2.** Upper panel:  $\lambda_d$  value as a function of redshift, showing the median  $\lambda_d$  value for each bin, using a constant stellar mass TF relation for the whole sample. The error bars in solid blue lines denote the estimated  $1\sigma$  confidence intervals for the mean based on the bootstrapping resampling method; the error bars in broken black lines denote the dispersion for each bin. Lower panel: same as the upper panel but using three different stellar mass TF relations valid on three redshift ranges delimited in Table 1.

**Table 1.** Stellar mass TF relations.

Redshift range	$a$	$b$
$0.2 \leq z \leq 1.2$	1.718	3.869
$0.2 \leq z \leq 0.5$	1.755	Fixed
$0.5 \leq z \leq 0.8$	1.684	Fixed
$0.8 \leq z \leq 1.2$	1.720	Fixed

late-type galaxies. These appear as soon as the galaxies cross into their virial radii, leading to a gradual decrease in the values of  $\lambda$ , especially when the neighbour galaxy is a spiral galaxy. For the galaxies in our sample, we also test the influence of the small-scale environment. Fig. 4 (upper panel) shows  $\lambda_d$  as a function of the distance to the nearest-neighbour galaxy normalized by the virial radius of the nearest neighbour as computed using equation (7). In this case, we note a decrease in the spin only for the most inner bin, but given the small number of galaxies involved, the result is also compatible with no dependence on the distance to the nearest-neighbour galaxy. For SDSS galaxies, we previously noticed (see fig. 4 in Cervantes-Sodi et al. 2010) that the decrease in the spin



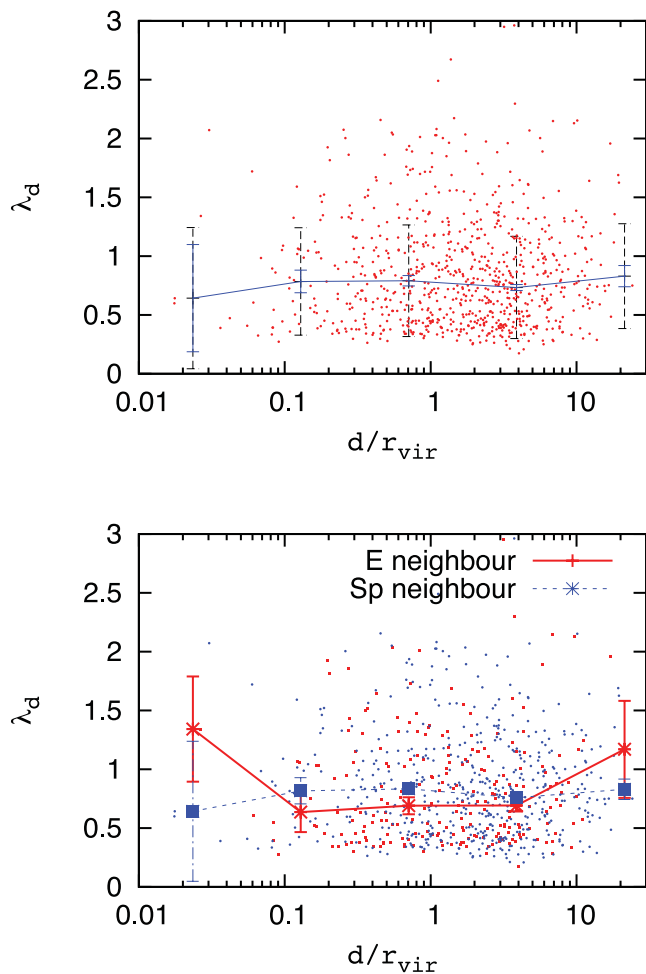
**Figure 3.** Correlation between the disc spin parameter and stellar mass (upper panel) and that between the disc spin parameter and environmental density  $\Sigma_5$  (lower panel).

depends on the morphology of the neighbour galaxy. With this in mind we segregated the galaxies in our high- $z$  sample according to the morphology of the neighbour galaxy to search for any difference on the value of  $\lambda_d$ . Fig. 4 (lower panel) shows the result, with only a significant difference for the case of  $d < 0.1r_{\text{vir}}$ , with a decrease in the  $\lambda_d$  value for the case of late-type neighbour and an increase for the case of early-type neighbour, a similar behaviour to the one observed with low-redshift galaxies, but given the small numbers involved it is difficult to reach a statistically meaningful conclusion at the moment.

## 5 CONCLUSIONS

Using a simple dynamical model, we have obtained empirical  $\lambda$  distributions of high-redshift galaxies in the range  $0.4 \leq z \leq 1.2$  that are compatible with results at low redshift.

Analysing the angular momentum of the disc component, we did not find traces of evolution as a function of redshift, and we were able to reproduce the relationships of the spin with mass and environment we found previously for local galaxies at all redshifts, showing a marked dependence of  $\lambda_d$  on the mass, with high-mass galaxies showing typically low  $\lambda_d$  values, as well as lower spread when compared with low-mass galaxies, while there is little if any dependence of  $\lambda_d$  on environment, either the large-scale or



**Figure 4.** Upper panel:  $\lambda_d$  as a function of the distance to the nearest-neighbour galaxy normalized by the virial radius of the neighbour galaxy. Lower panel: same as the upper panel having segregated the target galaxies according to the morphology of their nearest neighbour. In this case, we do not present the dispersion on each bin for clarity.

small-scale environmental parameter. These results led us to conclude that the spin parameter of disc galaxies suffers negligible evolution if any at all over the last 8 Gyr, which is a result in good agreement with theoretical expectations (Peirani, Mohayaee & de Freitas Pacheco 2004; Kimm et al. 2011), where most of the specific angular momentum is imprinted at early stages (e.g. White 1984, Barnes & Efstathiou 1987, Catelan & Theuns 1996, Pichon et al. 2011), followed by mild evolution, with rare drastic changes appearing only in the case of major mergers (e.g. Peirani et al. 2004, D’Onghia & Navarro 2007). As shown by high-resolution cosmological simulations (e.g. Governato et al. 2007; Brook et al. 2012), a relatively quite merging history also helps to form realistic disc galaxies. In addition, independent observational results suggest that most disc galaxies are dynamically mature by  $z \sim 1$  (Miller et al. 2012) in order to reproduce the stellar mass TF relation that is already in place at that redshift.

Finally, our results complement previous findings where different groups have shown that the baryonic specific angular momenta of disc galaxies at intermediate (Puech et al. 2007; Vergani et al. 2012) and high redshift, nearly  $z \sim 2$  (Förster Schreiber et al. 2006) or even  $z \sim 3$  (Nesvadba et al. 2006), are comparable to those of local late-type galaxies. Our study thus bridges the gap between local samples

and existing  $z \sim 2-3$  results. The consistent conclusions across all redshift ranges essentially rule out any significant dynamical evolution for large disc galaxies over the last 8–10 Gyr.

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