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ENVIRONMENT AND MASS DEPENDENCIES OF GALACTIC λ SPIN PARAMETER: COSMOLOGICAL SIMULATIONS AND SDSS GALAXIES COMPARED

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RESUMEN

Empleamos una muestra de galaxias del Sloan Digital Sky Survey (SDSS) para buscar correlaciones entre el parámetro de espín λ y el medio ambiente y la masa de las galaxias. Para calcular el valor total de λ de cada galaxia observada, empleamos un modelo sencillo de la estructura dinámica de las galaxias el cual nos permite una estimación a primer orden del valor de λ usando únicamente observables fácilmente medibles de galaxias luminosas. El uso de una muestra extensa limitada por volumen (más de 11,000), permite inferencias confiables de los valores medios y las correspondientes dispersiones de distribuciones de λ. Encontramos, en acuerdo con algunas simulaciones cosmológicas de N-cuerpos, que no hay una dependencia significativa de λ con la densidad del medio ambiente de las galaxias. En el caso de la masa, nuestros resultados muestran una fuerte correlación con λ, en el sentido que las galaxias de baja masa presentan tanto altos valores medios de λ como dispersiones asociadas respecto a galaxias masivas. Este último resultado empírico, en franco desacuerdo con resultados de simulaciones cosmológicas de N-cuerpos, provee constricciones interesantes a los mecanismos de formación galáctica y adquisición de momento angular, una prueba valiosa para modelos cosmológicos.

ABSTRACT

We use a sample of galaxies from the Sloan Digital Sky Survey (SDSS) to search for correlations between the λ spin parameter and the environment and mass of galaxies. In order to calculate the total value of λ for each observed galaxy, we employ a simple model of the dynamical structure of the galaxies which allows a rough estimate of the value of λ using only readily obtainable observables from the luminous galaxies. Use of a large volume limited sample (upwards of 11,000) allows reliable inferences of mean values and dispersions of λ distributions. We find, in agreement with some N-body cosmological simulations, no significant dependence of λ on the environmental density of the galaxies. For the case of mass, our results show a marked correlation with λ, in the sense that low mass galaxies present both higher mean values of λ and associated dispersions, than high mass galaxies. This last direct empirical result, at odds with expectations from N-body cosmological simulations, provides an interesting constraint on the mechanisms of galaxy formation and acquisition of angular momentum, a valuable test for cosmological models.

Key Words: cosmology: observations — galaxies: formation — galaxies: statistics — galaxies: structure

1. INTRODUCTION

One of the most studied parameters in numerical simulations of formation and evolution of galaxies, is the λ spin parameter, first introduced by Peebles in 1969, where it was used to test the gravitational instability picture, as a theory for the origin of galactic angular momentum. Since then, there have been several studies using the λ parameter as an indispensable tool of analysis, or characterizing its distribution in cosmological N-body simulations. In general, the distribution of this parameter, coming from numerical simulations, is well fitted by a log-normal distribution, characterized by two parameters; λ_0, the most probable value, and σ_λ, which accounts for the spread of the distribution. In a recent work, Shaw et al. (2006) showed a compilation of results for estimates of these parameters, arising from numerical studies performed by several authors, lying in the ranges: $0.03<\lambda_0<0.05$ and $0.48<\sigma_\lambda<0.66$, and some of us in a previous work (Hernández et al. 2007), using the same sample of 11 597 galaxies from the Sloan Digital Sky Survey (SDSS) we treated here, obtained the distribution of this parameter, with results well fitted by a log-normal function with parameters $\lambda_0 = 0.04 \pm 0.005$ and $\sigma_\lambda = 0.51 \pm 0.05$, for the first time derived from a statistical sample of real galaxies.

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With the recent explosion of high resolution cosmological simulations, studies concerning the spin parameter began to explore dependencies of the λ parameter with other physical parameters, mainly the total mass of the galaxy and the environment in which the galaxy is immersed. The results are as varied as the techniques employed to perform and analyse the simulations, but there is good agreement that for the case of a λ-environment relation, it should be very weak or inexistent (Bett et al. 2007; Maccio et al. 2007). The case of the λ-mass relation presents more discrepancies between results coming from different groups, some claiming the existence of a weak relation (Jang-Codell & Hernquist 2001; Bett et al. 2007) and others not finding any (Maccio et al. 2007). The aim of the present work is to derive distributions of the spin parameter as functions of mass and environment, using a first order estimate of galactic halo λ applied to a large sample of galaxies from the Sloan Digital Sky Survey (SDSS), in order to constrain and theories of angular momentum acquisition and galaxy formation.

2. THEORETICAL FRAMEWORK

The angular momentum is commonly characterized by the dimensionless spin parameter:

$$\lambda = \frac{L \mid E \mid^{1/2}}{G M^{5/2}} , \tag{1}$$

where E, M and L are the total energy, mass and angular momentum of the configuration, respectively. In Hernández & Cervantes-Sodi (2006), we derived a simple estimate of λ for disk galaxies, using a simple model employing two components to describe the galaxy, a disk for the barionic component with an exponential surface mass density $\Sigma(r)$;

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

where r is a radial coordinate and Σ_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;

$$\rho(r) = \frac{1}{4\pi G}\left(\frac{V_d}{r}\right)^2 . \tag{3}$$

We assume: (1) that the specific angular momentum of the disc and halo are equal e.g. Fall & Efstathiou (1980); (2) the total energy is dominated by that of the halo which is a virialized gravitational structure; (3) the disc mass is a constant fraction of the halo mass $F = M_d/M_H$. Introducing a Tully-Fisher relation and fixing constants with Galactic parameters, we obtain:

$$\lambda = 21.8 \frac{R_d/\mathrm{kpc}}{(V_d/\mathrm{km\ s^{-1}})^{3/2}} . \tag{4}$$

The above equation allows a direct estimate of λ for any disk galaxy. The corresponding equation for elliptical galaxies was derived in Hernández et al. (2007) modeling two components; a barionic matter distribution with a Hernquist density profile and a dark matter halo showing no difference from that of disk galaxies (Treu et al. 2006). Considering the structure of the galaxy as virialized, the mass is obtained in terms of the half light radius and the velocity dispersion σ. By dimensional analysis, the specific angular momentum is characterized by $(GM_b a)^{1/2}$, where M_b is the baryonic mass and a is the mayor axis. Introducing a numerical factor to account for the dissipation of the baryonic component, its dynamical pressure support and the projection effects, we finally obtain

$$\lambda = \frac{0.1173 e (a/\mathrm{kpc})^{2/7}}{(\sigma/\mathrm{km\ s^{-1}})^{3/7}} . \tag{5}$$

The accuracy of equation (4), was tested in Cervantes-Sodi et al. (2008), making use of numerical simulations, showing an agreement between the estimate and the real value of λ always better than 30 per cent, in most cases much better.

3. COMPARISONS OF λ DISTRIBUTIONS FROM THE SDSS AND COSMOLOGICAL N-BODY SIMULATIONS

3.1. *Observational sample*

The sample of real galaxies employed for the study comes from the SDSS Data Release 5 (Adelman-McCarthy et al. 2007). It is a volume limited sample having galaxies in the redshifts interval $0.025 < z < 0.055$ and absolute magnitudes $M_r - 5 \log h \leq -18.5$. Since most of the studies concerning spin distributions from simulations presents their results at $z = 0$, we limited the sample to low redshifts. This sample contains 32 550 galaxies for which Choi, Park, & Vogeley (2007) have determined the exponential disc scales, absolute magnitudes, velocity dispersions, de Vacouleurs radii and seeing corrected isophotal ellipticities for each galaxy, assuming a ΛCDM universe with $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$ and $h = 0.71$. To obtain λ for each galaxy, we need to discriminate between elliptical and disc galaxies; in order to do that we used the prescription of Park

& Choi (2005), in which early (ellipticals and lenticulars) and late (spirals and irregulars) types are segregated in a $u-r$ colour versus $g-i$ colour gradient space and in the concentration index space. In order to apply equation (4) to the disc galaxies of the sample, we need the rotation velocity, which is inferred from the absolute magnitude using a TF relation; then, to avoid the problem of internal absorption in edge-on galaxies, we employed only spiral galaxies having axis ratios > 0.6 and inferred rotation velocities in the range of $80 < V_R < 430$, well within the range of applicability of the TF relation we are using. After applying these two cuts, and removing a randomly selected fraction of ellipticals, so as to maintain the original early to late type fraction, we are left with a total of 11 597 galaxies.

For the elliptical galaxies we apply equation (5), as fully described in Hernández et al. (2007), using the corrected isophotal ellipticities to calculate the eccentricity.

3.2. *Simulation & Subhalo Finding*

To compare our observational sample with a numerical simulation, we have made a cosmological N-body simulation of a ΛCDM model, Dutton, A. A., van den Bosch, F. C., Morre, B., Potter, D., & Stadel, J., in a cubic box with the side length of $614h^{-1}$Mpc. The model parameters are $h = 0.7$, $\Omega_m = 0.27$, $\Omega_b = 0.046$, and $\Omega_\Lambda = 0.73$, given by the WMAP 1-year data (Spergel et al. 2003). The simulation gravitationally evolved 1024^3 CDM particles from redshift $z = 48$ to $z = 0$ taking 1880 global time steps. The linear density fluctuations of matter at the present epoch is normalized by $\sigma_8 = 0.9$, the RMS density fluctuation at $8h^{-1}$Mpc for a tophat window function. The mass of each simulation particle is $M_p = 1.4 \times 10^{10} h^{-1}\ M_\odot$ and the force spatial resolution is about $60h^{-1}$ kpc.

To identify subhalos in the simulation, we first extracted the dark matter particles located in virialized regions by applying the standard Friend-of-Friend (FoF) method with a linking length equal to one fifth the mean particle separation. This length is a characteristic scale for the identification of virialized structures. To each FoF particle group, we applied the PSB method (Kim & Park 2006) to find subhalos.

For comparisons with our observational results we randomly selected 100 000 halos from the simulation, for which the spin parameter λ was calculated numerically. The normalized local density parameter is obtained following the same method as used for our SDSS sample (for more details see Park et al. 2007).

4. RESULTS

To study if there is any correlation between spin and the environment, we use an estimation of the local background density defined directly from observations, that is continuous and able to characterize the full range of galaxy environments. It measures the local number density of galaxies at a given smoothing scale (Park et al. 2007). We divided both of our samples, the SDSS and the simulation, into 6 cuts according to the normalized environmental density $\rho/{<}\rho{>}$, and for each cut we obtained the mean λ value and its dispersion. The result is presented in Figure 1 left panels, where the value of total inferred λ versus $\rho/{<}\rho{>}$ for each galaxy is plotted and we show the mean λ value for each cut as a function of the normalized density. The solid error bars corresponds to the dispersion and the broken error bars to the standard error in the calculation of the mean value; this convention will be kept in the following figure. As can be seen, there is no clear trend, taking into account the dispersion in each bin, neither in the SDSS nor in the simulation sample.

On the right panels of Figure 1 are presented the plots of λ versus *mass* for the SDSS sample (top panel), and the simulation sample (bottom panel). We notice that for the SDSS sample, the mean value of λ tends to decrease as the mass increases. But not only the mean value, also the dispersion of λ tends to decrease as the value of the mass increases. The effect is stronger using only the disc galaxies, where our estimate is more precise (see Cervantes-Sodi et al. 2008). Large galaxies are seen to form a more coherent low λ sample with small dispersion, while small galaxies show mean values of λ of about a factor of 3 larger than what is found for our most massive galaxies. The dispersion about mean values shows the same trend, with small galaxies in our SDSS sample having a much larger dispersion than the large galaxies. The trend is not reproduced by the simulation used in this work, and neither has it ever been reported, to the large extent seen in the SDSS sample, in any cosmological N-body simulation found in the literature. However, precisely such a trend was recently confirmed by Berta et al. (2008) using a sample of 52 000 galaxies from the SDSS employing a similar method as the described here to estimate λ. We take our results as evidence of a mechanism of acquisition of angular momentum for galaxies, where it is the ambient tidal field what torques up a halo, with little participation of repeated mergers. An extensive development of these ideas can be found in Cervantes-Sodi et al. (2008).

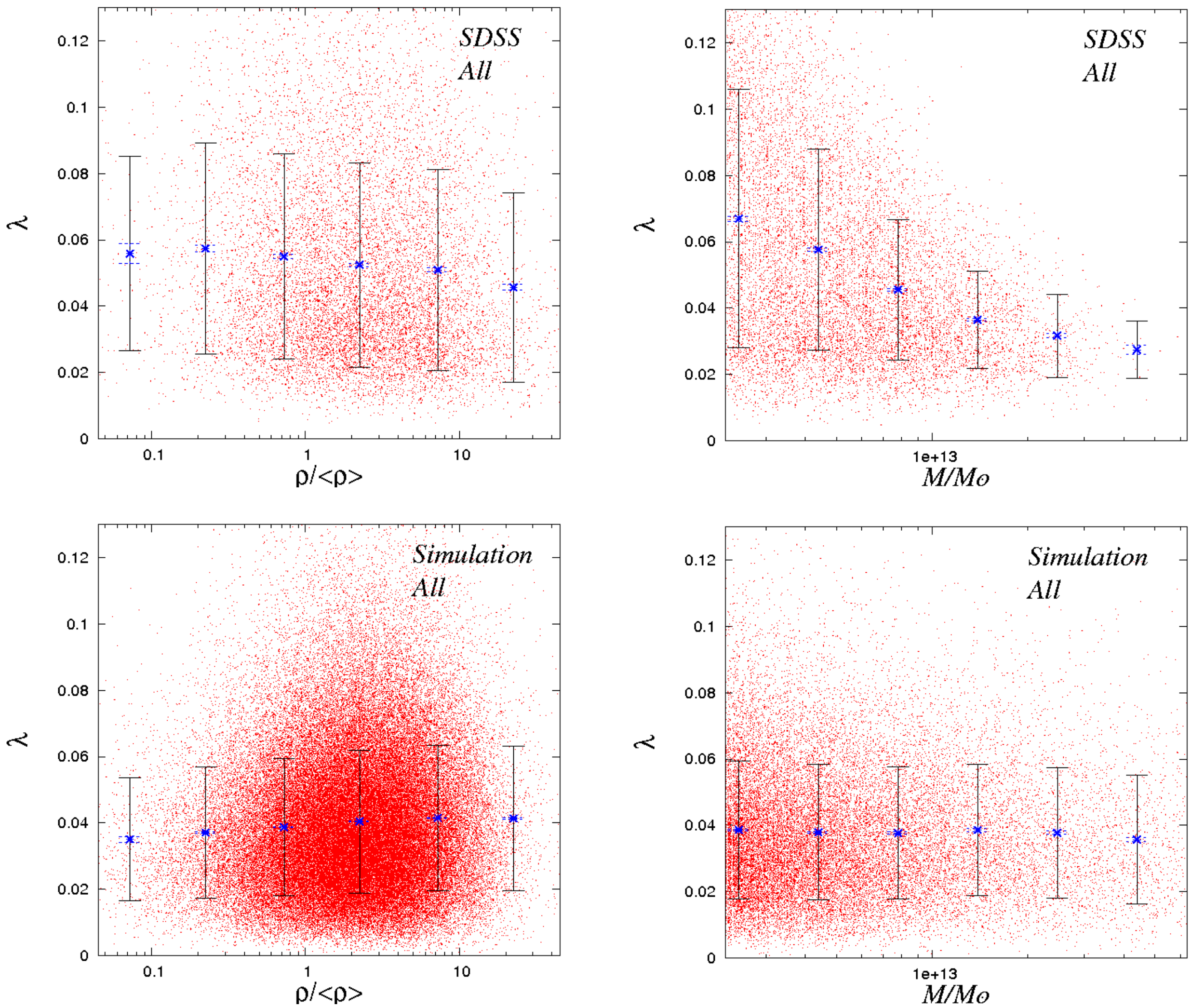

Fig. 1. Relations between galactic spin and environmental density and mass, showing the mean λ value for each bin as a function of the normalized density. The solid error bars correspond to the dispersion and the broken error bars to the standard error in the calculation of the mean value. *Top* panels correspond to the SDSS sample using the 11 597 galaxies, on the left-hand λ as a function of environmental density, on the right-hand λ as a function of mass. *Bottom* panels correspond to the sample of 100 000 simulated dark matter haloes, on the left-hand λ as a function of environmental density and on the right-hand as a function of mass.

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