A CORRELATION BETWEEN SPIN PARAMETER AND DARK MATTER HALO MASS

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Abstract. Using a set of high-resolution dark matter only cosmological simulations we found a correlation between the dark matter halo mass $M$ and its spin parameter $\lambda$ for objects forming at redshifts $z > 10$: the spin parameter decreases with increasing mass. However, halos forming at later times do not exhibit such a strong correlation, in agreement with the findings of previous studies.

While we presented such a correlation in a previous study using the Bullock et al. (2001) spin parameter definition we now defer to the classical definition showing that the results are independent of the definition.

1 Introduction

The physical mechanism by which galaxies acquire their angular momentum is an important problem that has been the subject of investigation for nearly sixty years (Hoyle 1949). This reflects the fundamental role played by angular momentum of galactic material in defining the size and shapes of galaxies (e.g. Fall & Efstathiou 1981). Yet despite its physical significance, a precise and accurate understanding of the origin of galactic angular momentum remains one of the missing pieces in the galaxy formation puzzle.

A fundamental assumption in current galaxy formation models is that galaxies form when gas cools and condenses within the potential wells of dark matter halos (White & Rees 1978). Consequently it is probable that the angular momentum of the galaxy will be linked to the angular momentum of its dark matter halo (e.g. Fall & Efstathiou 1980; Mo, Mao & White 1998; Zavala, Okamoto & Frenk 2007). Within the context of hierarchical structure formation models, the angular momentum growth of a dark matter proto-halo is driven by gravitational tidal torquing during the early stages (i.e. the linear regime) of its assembly.
This “Tidal Torque Theory” has been explored in detail; it is a well-developed analytic theory (e.g. Peebles 1969, Doroshkevich 1979, White 1984) and its predictions are in good agreement with the results of cosmological N-body simulations (e.g. Barnes & Efthathiou 1987; Warren et al. 1992; Sugerman, Summers & Kamionkowski 2000; Porciani, Dekel & Hoffman 2002). However, once the proto-halo has passed through maximum expansion and the collapse has become non-linear, tidal torquing no longer provides an adequate description of the evolution of the angular momentum (White 1984), which tends to decrease with time. During this phase it is likely that merger and accretion events play an increasingly important role in determining both the magnitude and direction of the angular momentum of a galaxy (e.g. Bailin & Steinmetz 2005). Indeed, a number of studies have argued that mergers and accretion events are the primary determinants of the angular momenta of galaxies at the present day (Gardner 2001; Maller, Dekel & Somerville 2002; Vitvitska et al. 2002).

It is common practice to quantify the angular momentum of a dark matter halo by the dimensionless “classical” spin parameter (Peebles 1969),

$$\lambda = \frac{J \sqrt{|E|}}{GM^{5/2}}.$$  

(1.1)

where $J$ is the magnitude of the angular momentum of material within the virial radius, $M$ is the virial mass, and $E$ is the total energy of the system. It has been shown that halos that have suffered a recent major merger will tend to have a higher spin parameter $\lambda$ than the average (e.g. Hetznecker & Burkert 2006; Power, Knebe & Knollmann 2008). Therefore one could argue that within the framework of hierarchical structure formation that higher mass halos should have larger spin parameters on average than less massive systems because they have assembled a larger fraction of their mass (by merging) more recently.

However, if we consider only halos in virial equilibrium, should we expect to see a correlation between halo mass and spin? One might naively expect that more massive systems will have had their maximum expansion more recently and so these systems will have been tidally torqued for longer than systems that had their maximum expansion at earlier times. This suggests that spin should increase with timing of maximum expansion and therefore halo mass. However, one finds at best a weak correlation between mass and spin for equilibrium halos at $z=0$ (e.g. Cole & Lacey 1996; Bett et al. 2007), and the correlation is for spin to decrease with increasing halo mass, contrary to our naive expectation.

2 The Data

For the simulations presented here we have adopted the cosmology as given by Spergel et al. (2003) ($\Omega_0 = 0.3$, $\Omega_{\Lambda} = 0.7$, $\sigma_8 = 0.9$, and $H_0 = 70$ km/sec/Mpc). Each run employed $N = 256^3$ particles and differed in simulation box-size $L_{\text{box}}$, which leads to the particle mass $m_p$ differing between runs – $m_p = \rho_{\text{crit}}\Omega_0(L_{\text{box}}/N)^3$, where $\rho_{\text{crit}} = 3H_0^2/8\pi G$. This allows us to probe a range of halo masses at redshift $z=10$. Halos in all runs have been identified using the MPI version of the
AHF halo finder\(^1\) (AMIGA's-Halo-Finder), which is based on the MHF halo finder of Gill, Knebe & Gibson (2004). Because we wish to examine the spin distribution of equilibrium halos, it is important to account for unrelaxed systems when investigating correlations between spin and halo mass. For an elaborate discussion of our relaxation criterion as well as more details about the simulations and halos we refer the reader to the original paper (Knebe & Power 2008).

3 Correlation between Spin and Mass

While in Knebe & Power (2008) we used the spin-parameter \(\lambda' = J/\sqrt{2} MVR\) as defined by Bullock et al. (2001) we show results in this contribution based upon the classical spin-parameter definition as given by Eq. (1.1). Therefore, the work presented here can be seen complementary to the original study of Knebe & Power (2008) and confirms that the findings are independent of the spin-parameter definition.

In Figure 3, we investigate the correlation between halo spin \(\lambda\) and mass \(M\). The best fitting power-laws to these histograms reveal that \(\lambda \propto M^\alpha\) with

\[
\begin{align*}
\alpha &= -0.006 \pm 0.146 \quad \text{for } z = 1 \\
\alpha &= -0.047 \pm 0.168 \quad \text{for } z = 10 .
\end{align*}
\]

This indicates that there is a weak correlation at high redshifts for spin to decrease with increasing mass, albeit stronger than the one at \(z=1\).

4 Conclusions

We have performed an investigation of the relation between virial mass and dimensionless spin parameter for dark matter halos forming at high redshifts \(z > 10\)

\(^1\)AHF is already freely available from http://www.aip.de/People/aknebe
in a ΛCDM cosmology. The result of our study, which is based on a series of cosmological N-body simulations in which box size was varied while keeping particle number fixed, indicates that there is a weak correlation between mass and spin at $z=10$, such that the spin decreases with increasing mass. If there is a correlation at $z=1$, we argue that it is significantly weaker than the one we find at $z=10$; this is in qualitative agreement with the findings of previous studies that focused on lower redshifts (Maccio et al. 2007, Shaw et al. 2005, Lemson & Kauffmann 1999).

While we presented such a correlation in a previous study (Knebe & Power 2008) using the Bullock et al. (2001) spin parameter definition we now deferred to the classical definition showing that the results are independent.

References

Barnes, J.; Efstathiou, G.; 1987, ApJ 319, 575
Bett, P.; Eke, V.; Frenk, C.S.; Jenkins, A.; Helly, A.; Navarro, J.; 2007, MNRAS 376, 215
Bullock, J., Dekel, A., Kolatt, T.S., Kravtsov, A.V., Klypin, A.A., Prochian, C., Primack, J.R., 2001, ApJ, 555, 240
Cole, S.; Lacey, C.; 1996, MNRAS 281, 726
Doroshkevich, A.G. 1973, Astrophys. Lett., 14, 11
Fall S. M. & Efstathiou G. 1980, MNRAS, 193, 189
Gardner, J.P.; 2001, ApJ 557, 616
Gill, S.P.D.; Knebe, A.; Gibson, B.K.; 2004, MNRAS 351, 399
Hetznecker, H.; Burkert, A.; 2006, MNRAS 370, 1905
Hoyle, F. 1945, MNRAS, 105, 287
Knebe A., Power C., ApJ 678, 621
Lemson, G.; Kauffmann, G.; 1999, MNRAS 302, 111
Maccio, A.V.; Dutton, A.A.; van den Bosch, F.C.; Moore, B.; Potter, D.; Stadel, J.; 2007, MNRAS 378, 55
Maller, A.H.; Dekel, A.; Somerville, R.; 2002, MNRAS 329, 423
Mo, H.J.; Mao, S.; White, S.D.M.; 1998, MNRAS 295, 319
Peebles, J. 1969, ApJ, 155, 393
Power, C.B.; Knebe, A.; Knollmann, S.; 2008, MNRAS submitted
Porciani, C., Dekel, A., Hoffman, Y. 2002, MNRAS, 332, 325
Shaw, L.D.; Weller, J.; Ostriker, J.P.; Bode, P.; 2006, ApJ 646, 815
Spergel, D.; et al.; 2003, ApJS, 148, 175
Sugerman, B., Summers, F. J., Kamionkowski, M. 2000, MNRAS, 311, 762
Vitvitska, M.; Klypin, A.A.; Kravtsov, A.V.; Wechsler, R.H.; Primack, J.R.; Bullock, J.S.; 2002, ApJ 581, 799
Warren, M. S., Quinn, P. J., Salmon, J. K., Zurek, W. H. 1992, ApJ, 399, 405
White, S.D.M. & Rees, M. 1978, MNRAS, 183, 341
White, S.D.M.; 1984
Zavala J., Okamoto T. & Frenk. C. S. astro-ph/0710.2901