Subhaloes gone Notts: spin across subhaloes and finders

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ABSTRACT
We present a study of a comparison of spin distributions of subhaloes found associated with a host halo. The subhaloes are found within two cosmological simulation families of Milky Way-like galaxies, namely the Aquarius and GHALO simulations. These two simulations use different gravity codes and cosmologies. We employ 10 different substructure finders, which span a wide range of methodologies from simple overdensity in configuration space to full 6D phase space analysis of particles. We subject the results to a common post-processing pipeline to analyse the results in a consistent manner, recovering the dimensionless spin parameter. We find that spin distribution is an excellent indicator of how well the removal of background particles (unbinding) has been carried out. We also find that the spin distribution decreases for substructures the nearer they are to the host haloes, and that the value of the spin parameter rises with enclosed mass towards the edge of the substructure. Finally, subhaloes are less rotationally supported than field haloes, with the peak of the spin distribution having a lower spin parameter.

Key words: galaxies: evolution – galaxies: haloes – cosmology: theory – dark matter.

1 INTRODUCTION
Within the hierarchical galaxy formation model, dark matter haloes are thought to play the role of gravitational building blocks, within which baryonic diffuse matter collapses and becomes detectable (White & Rees 1978; White & Frenk 1991). Gravitational processes that determine the abundance, the internal structure and kinematics, and the formation paths of these dark haloes within the cosmological framework can be simulated in great detail using \( N \)-body methods. However, the condensation of gas associated with these haloes, eventually leading to stars and galaxies we see today, is still at the frontier of present research efforts. A first exploration of the (cosmological) formation of disc galaxies has been presented in Fall & Efstathiou (1980), where it was shown that galactic spin is linked to the surrounding larger scale structure (e.g. the parent halo). In particular, the general theory put forward by Fall & Efstathiou reproduces galactic discs with roughly the right sizes, if specific angular momentum is conserved, as baryons contract to form a disc (previously suggested by Mestel 1963) and if baryons and dark matter initially share the same distribution of specific angular momentum.

While the theory has subsequently been refined, it always included (and still includes) such a coupling between the parent halo’s angular momentum and the resulting galactic disc (cf. Dalcanton, Spergel & Summers 1997; Mo, Mao & White 1998; Navarro &
Steinmetz 2000; Abadi et al. 2003; Bett et al. 2010). The origin of the halo’s spin can now be understood in terms of tidal torque theory in which protohaloes gain angular momentum from the surrounding shear field (e.g. Peebles 1969; White 1984; Barnes & Efstathiou 1987) as well as by the build-up of angular momentum through the cumulative transfer of angular momentum from subhalo accretion (Vivitska et al. 2002). Whichever way the halo gains its spin, it is a crucial ingredient for galaxy formation and all semi-analytical modelling of it (Kauffmann, White & Guiderdoni 1993; Frenk et al. 1997; Kauffmann, Nusser & Steinmetz 1997; Cole et al. 2000; Benson et al. 2001; Bower et al. 2006; Croton et al. 2006; Bertone, De Lucia & Thomas 2007; De Lucia & Blaizot 2007; Font et al. 2008; Benson 2012).

A number of studies have been performed on the spin of haloes, in particular studies by Peebles (1969), Bullock et al. (2001), Hetznecker & Burkert (2006), Bett et al. (2007), Macciò et al. (2007), Gottlöber & Yepes (2007), Knebe & Power (2008), Antonuccio-Delogu et al. (2010), Wang et al. (2011), Trowland, Lewis & Bland-Hawthorn (2013), Lacerna & Padilla (2012) and Bryan et al. (2012) but so far little has been done on subhaloes. These studies look at the spin of individual dark matter haloes found in cosmological simulations and generally do not focus on the substructure, or differences between substructure definition due to lack of resolution. Here, we present a comparison of spin parameters across a number of detected subhaloes found by a variety of substructure finders. The finders use many different techniques to detect substructure within a larger host halo. This is a follow-up to a more general paper comparing the recovery of structure by different finders in Onions et al. (2012) and its predecessor Knebe et al. (2011).

The techniques studied here for finding substructures include real-space, phase-space, velocity-space finders, as well as finders employing a Voronoi tessellation, tracking haloes across time using snapshots, friends-of-friends techniques and refined meshes as the starting point for locating substructure. With such a variety of mechanisms and algorithms, there is little chance of any systematic source of errors in the collection of substructure distorting the result. Subhaloes are particularly subject to distortion and evolution, more than haloes because, by definition, they reside within a host halo with which they tidally interact. This can affect their structure and other parameters, and in this case we are particularly interested in the spin properties. We quantify the spin with the parameter \(\lambda\), a dimensionless quantity that characterizes the spin properties of a halo and is explained in more detail in Section 2.

The rest of the paper is structured as follows. We first describe the methods used to quantify the spin of the halo in Section 2. The data we used are described in Section 3. Next, we look at the overall properties of the spin in Section 4.1. Then we look at the correlation between the host halo and the subhaloes spin in Section 4.2. Finally, we look at how the spin is built up within the subhalo as a function of mass in Section 4.3. We conclude in Section 5.

2 METHOD

2.1 Spin parameter

The dimensionless spin parameter gives an indication of how much a gravitationally bound collection of particles is supported in equilibrium via net rotation compared to its internal velocity dispersion. The spin parameter varies in the range 0, for a structure negligibly supported by rotation, to values of order 1 where it is completely rotationally supported, and in practice maximum values are usually \(\lambda \approx 0.4\) (Frenk & White 2012). Values larger than 1 are unstable structures not in equilibrium.

There are two variants of the spin parameter that are in common use. Peebles (1969) proposed to parametrize the spin using the expression given in equation (1)

\[
\lambda = \frac{J\sqrt{|E|}}{GM^{5/2}} \tag{1}
\]

where \(J\) is total angular momentum, \(E\) the energy and \(M\) the mass of the structure. In isolated haloes, all of these quantities are conserved, which gives the definition a time independence.

Bett et al. (2007) measured the Peebles’ spin parameter and fitted an expression to the distribution for haloes extracted from the Millennium simulation (Springel et al. 2005); that is characterized by equation (2)

\[
P(\log \lambda) = A \left(\frac{\lambda}{\lambda_0}\right)^3 \exp \left[-\alpha \left(\frac{\lambda}{\lambda_0}\right)^{3/\alpha}\right] \tag{2}
\]

where \(A\) is

\[
A = 3 \ln 10 \frac{\alpha^{\alpha-1}}{\Gamma(\alpha)}. \tag{3}
\]

The variables \(\lambda_0\) and \(\alpha\) are free parameters, and \(\Gamma(\alpha)\) is the gamma function. The best fit they found for field haloes was with \(\lambda_0 = 0.04326\) and \(\alpha = 2.509\).

Bullock et al. (2001) proposed a different definition of the spin parameter, \(\lambda'\), expressed in equation (4). As it is not dependent on measuring the energy it is somewhat faster to calculate when dealing with large numbers of haloes.

\[
\lambda' = \frac{J}{\sqrt{2MRV}} \tag{4}
\]

where, \(J\) is the angular momentum within the enclosing sphere of virial radius \(R\) and virial mass \(M\), and \(V\) is the circular velocity at the virial radius \(V^2 = GM/R\). The Bullock spin parameter is more robust to the position of the outer radius of the structure. Bullock proposes a fitting function to the distribution as described in equation (5) which was based on one from Barnes & Efstathiou (1987).

\[
P(\lambda') = \frac{1}{\lambda' \sqrt{2\pi \sigma}} \exp \left(-\frac{\ln^2(\lambda'/\lambda_0)}{2\sigma^2}\right) \tag{5}
\]

This has free parameters \(\lambda_0\) and \(\sigma\) and Bullock et al. (2001) found a best fit for field haloes at values of \(\lambda_0 = 0.035\) and \(\sigma = 0.5\).

The Peebles calculation is perhaps more well defined for a given set of particles, as it is calculated directly from the particles properties, whereas the Bullock parameter is easier to calculate from gross halo statistics, and is not dependent on the density profile. For more comparisons of the two parameters the reader is referred to Hetznecker & Burkert (2006).

2.2 The subhalo finders

In this section, we briefly list the halo finders that took part in the comparison project. More details about the specific algorithms are available in Onions et al. (2012) and the papers referenced therein.

(i) ADAPTAHOP (Tweed) is a configuration space over density finder (Aubert, Pichon & Colombi 2004; Tweed et al. 2009).

(ii) AHF (Knollmann & Knebe) is a configuration space spherical overdensity adaptive mesh finder (Gill, Knebe & Gibson 2004; Knollmann & Knebe 2009).
The group finding with GRASSHOPPER is now fast enough to allow it to be performed during a simulation but gives nearly identical results to the previous SKID algorithm.

(vi) Hierarchical Bound-Tracing (HBT) (Han) is a tracking algorithm working in the time domain (Han et al. 2012).

(vii) HOT+FIsEstAS (HOT3D & HOT6D) (Ascasibar) is a general-purpose clustering analysis tool, working either in configuration or phase space (Ascasibar & Binney 2005; Ascasibar 2010).

The participants were asked to run their subhalo finders on the supplied data and to return a catalogue listing the substructures they found. Specifically, they were asked to return a list of uniquely identified substructures together with a list of all particles associated with each subhalo. The broad statistics of the haloes found are summarized in Table 2.

To enable a direct comparison, all the data returned were subject to a common post-processing pipeline detailed in Onions et al. (2012). For this project, we added a common unbinding procedure based on the algorithm from the AHP finder which is based on spherical unbinding from the centre. We requested data to be returned both with and without unbinding to allow a comparison of that procedure to feature in this study. Unbinding is the process where the collection of gathered particles is examined to discard those which are not gravitationally bound to the structure. This common unbinding allowed us to remove some of the sources of scatter introduced by the finders using slightly different algorithms for removing unbound particles and to find what difference this made to the results.

Both the halo finder catalogues (alongside the particle ID lists) and our post-processing software are available from the authors on request.

4 RESULTS

The results used were restricted to subhaloes with more than 300 particles, as these produce a relatively stable value for spin. Values

\[ \Omega_M = 0.2669, \quad \Omega_\Lambda = 0.734, \quad \sigma_8 = 0.801, \quad n_s = 0.963, \quad h = 0.71 \]

Table 1. Summary of the key numbers in the Aquarius and GHALO simulations used in this study. \( N_{\text{high}} \) is the number of particles with the highest resolution (lowest individual mass). \( N_{250} \) is the number of high resolution particles found within a sphere of radius 250 kpc h\(^{-1}\) from the fiducial centre at each resolution (i.e. those of primary interest for this study).

<table>
<thead>
<tr>
<th>Simulation</th>
<th>( N_{\text{high}} )</th>
<th>( N_{250} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquarius-A</td>
<td>2316 893</td>
<td>712 232</td>
</tr>
<tr>
<td>Aquarius-A</td>
<td>1853 597</td>
<td>5715 467</td>
</tr>
<tr>
<td>Aquarius-A</td>
<td>148285 000</td>
<td>45150 166</td>
</tr>
<tr>
<td>Aquarius-A</td>
<td>531570 000</td>
<td>162527 280</td>
</tr>
<tr>
<td>Aquarius-A</td>
<td>4522607 000</td>
<td>1306256 871</td>
</tr>
<tr>
<td>Aquarius-A</td>
<td>18949 101</td>
<td>4771 239</td>
</tr>
<tr>
<td>Aquarius-A</td>
<td>26679 146</td>
<td>6423 136</td>
</tr>
<tr>
<td>Aquarius-A</td>
<td>20455 156</td>
<td>8327 811</td>
</tr>
<tr>
<td>Aquarius-A</td>
<td>17159 996</td>
<td>5819 864</td>
</tr>
<tr>
<td>GH-4</td>
<td>11254 149</td>
<td>1723 372</td>
</tr>
<tr>
<td>GH-3</td>
<td>141232 695</td>
<td>47005 813</td>
</tr>
</tbody>
</table>

3.2 Post-processing pipeline

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To enable a direct comparison, all the data returned were subject to a common post-processing pipeline detailed in Onions et al. (2012). For this project, we added a common unbinding procedure based on the algorithm from the AHP finder which is based on spherical unbinding from the centre. We requested data to be returned both with and without unbinding to allow a comparison of that procedure to feature in this study. Unbinding is the process where the collection of gathered particles is examined to discard those which are not gravitationally bound to the structure. This common unbinding allowed us to remove some of the sources of scatter introduced by the finders using slightly different algorithms for removing unbound particles and to find what difference this made to the results.

Both the halo finder catalogues (alongside the particle ID lists) and our post-processing software are available from the authors on request.

3 THE DATA

3.1 Simulation data

The first data set used in this paper forms part of the Aquarius project (Springel et al. 2008). It consists of multiple dark matter only resimulations of a Milky Way-like halo at a variety of resolutions performed using GADGET3 (based on GADGET2; Springel 2005). We have used in the main the Aquarius-A to E halo data set at \( z = 0 \) for this project. This provides five levels of resolution, varying in complexity for which further details are available in Onions et al. (2012).

The underlying cosmology for the Aquarius simulations is the same as that used for the Millennium simulation (Springel et al. 2005), i.e. \( \Omega_M = 0.25, \Omega_\Lambda = 0.75, \sigma_8 = 0.9, n_s = 1, h = 0.73 \). These parameters are close to the latest Wilkinson Microwave Anisotropy Probe (WMAP) data (Jarosik et al. 2011) (\( \Omega_M = 0.2669, \quad \Omega_\Lambda = 0.734, \quad \sigma_8 = 0.801, \quad n_s = 0.75 \)) although \( \sigma_8 \) is a little high. All the simulations were started at an initial redshift of 127. Precise details on the setup and performance of these models can be found in Springel et al. (2008).

The second data set was from the GHALO simulation data (Stadel et al. 2009). GHALO uses a slightly different cosmology to Aquarius, \( \Omega_M = 0.237, \quad \Omega_\Lambda = 0.763, \quad \sigma_8 = 0.742, n_s = 0.951, h = 0.735 \) which again are reasonably close to WMAP latest results. It also uses a different gravity solver, FIDGRAV2 (Stadel, Wadsley & Richardson 2002), to run the simulation therefore allowing comparison which is independent of gravity solver and to some extent the exact cosmology.

The details of both simulations are summarized in Table 1.

The group finding with GRASSHOPPER is now fast enough to allow it to be performed during a simulation but gives nearly identical results to the previous SKID algorithm.
Table 2. The number of subhaloes containing 300 or more particles and centres within a sphere of radius $250 \, \text{kpc} \, h^{-1}$ from the fiducial centre found by each finder after standardized post-processing (see Section 3.2).

<table>
<thead>
<tr>
<th>Name</th>
<th>ADAPTAHOP</th>
<th>AHF</th>
<th>GRASSHOPPER</th>
<th>HBT</th>
<th>HOT3D</th>
<th>HOT6D</th>
<th>MENDIETA</th>
<th>ROCKSTAR</th>
<th>STF</th>
<th>SUBFIND</th>
<th>VOBOZ</th>
</tr>
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<tbody>
<tr>
<td>Aq-A-5</td>
<td>24</td>
<td>23</td>
<td>23</td>
<td>23</td>
<td>18</td>
<td>23</td>
<td>17</td>
<td>25</td>
<td>22</td>
<td>23</td>
<td>21</td>
</tr>
<tr>
<td>Aq-A-4</td>
<td>222</td>
<td>189</td>
<td>170</td>
<td>169</td>
<td>174</td>
<td>176</td>
<td>123</td>
<td>182</td>
<td>155</td>
<td>154</td>
<td>163</td>
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<tr>
<td>Aq-A-3</td>
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<td>1259</td>
<td>1202</td>
<td>1217</td>
<td>–</td>
<td>–</td>
<td>787</td>
<td>1252</td>
<td>1124</td>
<td>1117</td>
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<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>25009</td>
<td>–</td>
<td>26155</td>
<td>–</td>
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<tr>
<td>Aq-B-4</td>
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<td>191</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>202</td>
<td>–</td>
<td>188</td>
<td>–</td>
</tr>
<tr>
<td>Aq-C-4</td>
<td>–</td>
<td>152</td>
<td>146</td>
<td>–</td>
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<td>–</td>
<td>158</td>
<td>–</td>
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<td>–</td>
</tr>
<tr>
<td>Aq-D-4</td>
<td>–</td>
<td>217</td>
<td>216</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>230</td>
<td>–</td>
<td>196</td>
<td>–</td>
</tr>
<tr>
<td>Aq-E-4</td>
<td>–</td>
<td>218</td>
<td>219</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>221</td>
<td>–</td>
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<td>–</td>
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<td>GH-4</td>
<td>–</td>
<td>58</td>
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<td>–</td>
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<td>54</td>
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<tr>
<td>GH-3</td>
<td>–</td>
<td>1172</td>
<td>1148</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1148</td>
<td>1033</td>
<td>1090</td>
<td>–</td>
</tr>
</tbody>
</table>

below this limit tend not to converge across resolutions (Bett et al. 2007).

4.1 Spin parameter

In general, there is a proportional relationship between the Peebles and Bullock spin parameters recovered by all the finders for the same subhaloes, although there is some scatter as shown in Fig. 1. We do not dwell on the differences between the two definitions as that has already been studied elsewhere (Hetznecker & Burkert 2006). As both definitions of spin exist in the literature we consider both metrics when comparing how the spin is recovered across finders, placing particular emphasis on their application to subhaloes.

The majority of field haloes are found to cluster around a value of $\lambda_0 = 0.044$ for the Peebles spin parameter (Bett et al. 2007) and $\lambda'_0 = 0.035$ for the Bullock parameter (Bullock et al. 2001) with a spread of values matched by a free parameter to give the width of the distribution.

4.1.1 Spin for subhaloes with no unbinding performed

If unbinding has not been correctly implemented the high speed background particles can distort the spin parameter enormously.

To emphasize the type of structures that are found, an example of a subhalo without (left-hand panel) and with (right-hand panel) unbinding is shown in Fig. 2. This is displayed as a vector plot of all the component particles position and velocities that make up the subhalo with the velocity vectors scaled in the same way in both panels. The bulk velocity of the subhalo has been removed and all positions and velocities are relative to the rest frame of the subhalo. Evident in the left-hand panel of Fig. 2 without unbinding are stray particles that are part of the background halo. Despite their small number these particles have both a large lever arm and large velocity relative to the halo, and significantly alter the derived value of the spin parameter due to their large angular momenta.

Comparing the two forms of the spin parameter in Figs 3 and 4 we show how the spin parameter is quite chaotic, not matching a smooth Gaussian like profile as might be expected, and is clearly a long way removed from the idealized curve others have found for the distribution of spin. A significant number of the haloes have spin parameter values above 1, which is unphysical as these objects would be ripped apart by this level of rotation and so clearly cannot be equilibrium systems. This result is perhaps not surprising given the contribution from unbound background particles moving with velocities far from the mean of the object being considered but clearly shows how poor unbinding methods are relatively easy to
detect by looking at the spin parameter distribution. The Peebles spin parameter is more affected by the lack of unbinding than the equivalent Bullock parameter as it takes into account the kinetic energy of all the particles. Some more objective numbers for this and subsequent comparisons are given in Table 3.

The best-fitting values shown by the bold dashed lines are vastly different from the fiducial values given in Section 2. It is however significant that the finders HOT6D, ROCKSTAR and STF (shown by dotted lines), which all have a phase space based component in their particle collection algorithm already show a much better fit to the fiducial value than the non-phase-space finders. It should be noted that when GRASSHOPPER is run without unbinding, it finds a large number of subhaloes which would normally be discarded by the unbinding procedure that is integral to the final part of the GRASSHOPPER algorithm.

<table>
<thead>
<tr>
<th>Plot</th>
<th>$\lambda_0$</th>
<th>$\Delta \lambda_0$</th>
<th>Change (per cent)</th>
<th>$\sigma/\alpha$</th>
<th>$\Delta \sigma/\alpha$</th>
<th>Change (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BullockF</td>
<td>0.035</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peebles</td>
<td>0.044</td>
<td>2.509</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BullockN</td>
<td>1.646</td>
<td>1.611</td>
<td>+4600</td>
<td>1.36</td>
<td>0.86</td>
<td>172</td>
</tr>
<tr>
<td>PeeblesN</td>
<td>12.6</td>
<td>12.573</td>
<td>+29000</td>
<td>41</td>
<td>39.2</td>
<td>1560</td>
</tr>
<tr>
<td>BullockO</td>
<td>0.028</td>
<td>−0.007</td>
<td>−20</td>
<td>0.727</td>
<td>0.227</td>
<td>45.5</td>
</tr>
<tr>
<td>PeeblesO</td>
<td>0.028</td>
<td>−0.016</td>
<td>−36</td>
<td>3.643</td>
<td>1.134</td>
<td>45.2</td>
</tr>
<tr>
<td>BullockC</td>
<td>0.031</td>
<td>−0.004</td>
<td>−10.4</td>
<td>0.75</td>
<td>0.25</td>
<td>50.0</td>
</tr>
<tr>
<td>PeeblesC</td>
<td>0.03</td>
<td>−0.013</td>
<td>−30</td>
<td>3.96</td>
<td>1.448</td>
<td>57.7</td>
</tr>
<tr>
<td>Bullock-L1</td>
<td>0.022</td>
<td>−0.013</td>
<td>−38</td>
<td>0.693</td>
<td>0.193</td>
<td>38.6</td>
</tr>
</tbody>
</table>

4.1.2 Spin for subhaloes with finders own unbinding performed

Including each finder’s own unbinding procedure improves the spin parameter measure considerably, as shown in Figs 5 and 6. Note that as ADAPTAHOP does not do any unbinding in its post-processing steps it is a clear outlier on this plot. The MENDIETA finder shows a double peak, which is indicative of some of the unbinding failing, an issue that the authors of the finder are currently working on.

When fitting the best-fitting curves to this data obtained for the spin parameter of subhaloes, the peak of the Bullock fitting curve given in equation (4) is less than the field halo value by about 20 per cent, offsetting the mean towards smaller values of the spin parameter. For the Peebles spin parameter the best fit is again offset by about 36 per cent from the field halo value, again towards a smaller value of the spin parameter.

Figure 5. The same plot as Fig. 3 but with the finders own unbinding processing applied to the data. This groups the spin parameters somewhat more tightly, and shows that spin is a good indicator of how well the unbinding procedure is removing spurious background particles. The ADAPTAHOP finder does not perform an unbinding step, and this plot also shows up a flaw in MENDIETA’s unbinding procedure. The dashed line is the Bullock field halo fit curve from Bullock et al. (2001). The Bullock data fit is the best fit to the average using the Bullock fitting formula.
4.1.3 Spin for subhaloes with a common unbinding performed

Once a common unbinding is done, the curves move significantly closer to the idealized curve, although there is still some separation. The plots of Figs 7 and 8 compare the spin parameter distribution of the different finders using a common unbinding process. These plots show the match between the best-fitting curve quoted in Bullock et al. (2001) and Bett et al. (2007) and the haloes found by the finders taking part in the comparison. The values are now offset by 10 per cent for the Bullock fit and 30 per cent for the Peebles fit. This results in the closest fit to the data, although the subhalo spin again extends to slightly lower values for both parameters, and follows the best-fitting line at larger values. These results also have a similar trend for the Aquarius B–E haloes and the GHALO data sets. These inclusions show that the results are not influenced greatly by the simulation, simulation engine or small changes in the cosmology used.

4.1.4 Spin at higher resolutions

Going to higher resolutions afforded by the level 1 data as shown in Fig. 9, the trend to a lower spin distribution peak continues, although only three of the finders were able to manage such a computationally intensive task.

There is a more pronounced tendency to depart from the field halo fit line at low spin part of the distribution, with the peak and bulk of the distribution moving towards lower spin parameter values. The finders also show more scatter with each of them identifying the peak of the distribution in slightly different places. The agreement particularly at the low end of the spin distribution is good but with slightly lesser agreement at the high end.

Although AHF appears to find slightly more higher spin haloes, this is a result of the spherical unbinding algorithm it uses, which tends to also increase the spin distribution of the other finders slightly when used as the common unbinding procedure.

The dashed line representing the level 4 data is included to allow a direct comparison between the levels 4 and 1 average fits. It shows the continued movement of the distribution towards lower spin values with higher resolution and an increase in data.
4.1.5 Spin distribution summary

The best-fitting curve figures for all these plots are summarized in Table 3. Even after cleaning the catalogues significantly by utilizing a common unbinding procedure for all finders there remains a definite trend for substructure spin to be less than that found for field haloes. We investigate the reason for this in the next sections.

4.2 Host halo radial comparison

Next, we consider whether the location of a subhalo within a host halo has any effect on the recovered spin parameter. First, we demonstrate in Fig. 10 that any effect is not an artefact of the finding process. Substructures closer into the centre of the host halo are more difficult to detect particularly by some finders, and therefore subject to a loss of constituent particles that could be attached to the subhalo as shown in Muldrew, Pearce & Power (2011). To test this supposition, we took a subhalo found in the outskirts of the Aquarius-A main halo, and repositioned it at points closer to the location of the centre of the halo. Then two of the finders (AHF and ROCKSTAR) were rerun on the new data and the spin value calculated anew. The results shown in Fig. 10 indicate that there is little change in the value of the spin parameter with radius despite some variation in the recovered number of particles.

Next, we look at whether the mean value of the measured spin parameters changes with respect to the distance from the centre of the host halo. Fig. 11 displays this radial dependence for the indicated finders after a common unbinding step has been applied. The background points indicate the scatter in the spin parameter for any individual halo, as seen in the previous section. This shows a small trend for a lower mean spin as the subhaloes get closer to the centre of the host halo. This confirms the result that was found in Reed et al. (2004) but is shown here at higher resolution and across more finders than the earlier paper.

Equivalent results are found when we compare six different simulations generated by two different N-body codes and aggregate the average of the different finders across multiple haloes in Fig. 12. This effect (as noted in Reed et al. 2004) is difficult to detect observationally, as most substructure will form galaxies before falling in so will have its spin detectable from observations of galactic rotation curve already fixed (Kauffmann et al. 1993). The possible exception to this are galaxies forming at high redshift where the infalling substructure has not yet formed stars, such as gas-rich dark galaxies (Cantalupo, Lilly & Haehnelt 2012), made entirely of dark matter and gas, which may form structure after falling into a parent halo.

4.3 Build-up of the spin parameter within a subhalo

This leads to the question of what causes the drop in the measured spin parameter with proximity to the centre of the host halo. Fig. 13 shows the average change in the measured spin parameter as the detected subhalo is analysed from the centre outwards to its radius. This procedure is computed after the common processing and unbinding steps have been done. The subhaloes analysed in this way are then further binned into radial bins determined from the centre of the host halo. The outermost subhaloes, which are the least
and mass plots but show up in an
The radial profile of the spin parameter across the subhalo. This
tot
A comparison of the normalized mean Peebles spin at different
$R$ is the subhaloes maximum
$v$ at the subhaloes
value. Here,

serves as a mechanism to detect if substructure finders are perform-
finders unbinding ability and seems broadly unaffected by the cos-
stream like structures and some on simple overdensities. There is
that are being recovered by the finders, some finders focusing on
doubtedly, some of the scatter is due to different types of subhaloes
ery of the distribution of the spin of subhaloes, although differences

Figure 13. The radial profile of the spin parameter across the subhalo. This
shows the change in the measured spin parameter as spin is analysed from
the centre to the radius of the subhalo. Here, $R_{\text{max}}$ is the subhaloes maximum
radius. Each line represents a different host halo radial bin. Subhaloes near
the centre of the host halo show monotonically rising spin parameter values,
whereas further out the spin parameter initially drops before rising.
disrupted, show an initial decrease in measured spin parameter as
particles are removed from their outer edges. Subhaloes extracted
from nearer the centre of the host halo do not show this initial de-
crease but instead have a monotonically rising spin parameter as
material is removed.

This trend suggests that subhaloes are preferentially stripped of
high angular momentum particles which are likely to be the most
weakly bound particles, leading to a decrease in the spin parameter
as they enter the host halo. The outermost particles are usually those
least bound so are the most likely to be removed on infall.

We can also examine how the spin parameter is built up as mass
is added to a subhalo. In Fig. 14, we look at how the spin parameter
changes at various mass cuts of the subhalo, $M(< M_{\text{max}})$. This shows
how the spin is built up across the structure of the subhalo. For
each halo we calculate the spin parameter at 0.25, 0.5, 0.75 and 0.95 of
the subhalo’s total mass for all the contributing halo finders. We
plot the mean and the standard deviation at each mass cut.

As expected from Fig. 13 all finders agree that the calculated spin
increases as the fraction of the subhalo mass that is used to calculate
the spin parameter is reduced. Note that haloes have steeply rising
density profiles and so the inner 50 per cent of the mass is contained
within a much smaller fraction of the radius and that this result is
averaged over all the recovered haloes and not split in radial bins.

5 SUMMARY AND CONCLUSIONS

There is a good level of agreement amongst the finders on the recov-
ery of the distribution of the spin of subhaloes, although differences
are still evident, causing scatter in some of the comparisons. Un-
doubtedly, some of the scatter is due to different types of subhaloes
that are being recovered by the finders, some finders focusing on
stream like structures and some on simple overdensities. There is
still some room for improvement of the finders as the common un-
binding test shows. Some of the possible improvements and sources
of error will be outlined in Knebe et al. (in preparation).

The distribution of spin provides a very good indicator of the
finders unbinding ability and seems broadly unaffected by the cos-
mology and simulation engine in use. As such, the spin distribution
serves as a mechanism to detect if substructure finders are perform-
ing the unbinding correctly. The unbinding errors can be masked in
other comparisons such as $v_{\text{max}}$ and mass plots but show up in an
obvious way when the spin distribution is examined. Phase-space
finders are less sensitive to poor unbinding as they have some im-
plicit unbinding in their selection criteria when looking at velocity
components. Indeed Hetznecker & Burkert (2006) and D’Onghia &
Navarro (2007) both show that there is a good correlation between
the virialization of haloes and the spin parameter, thus indicating its
use for the determination of how relaxed the halo is, which is not
unrelated to the unbinding process.

The mean spin parameter of subhaloes decreases as they approach
the host halo’s centre. This is a real effect and not an artefact of
any difficulty in recovering structure as the subhalo approaches the
centre of the main halo. This effect is apparent in the spin parameter
distribution which matches that of field haloes at larger radii but has
a broader width than other published fits, extending to lower spin
values. This difference between the spin properties of subhaloes and
field haloes needs to be taken into account if precise measurements
of the spin parameter distribution are to be made.

The recovered spin parameter goes through a minimum for sub-
haloes near the edge of the host at about half the $r_{\text{max}}$ value. Here,
if outer particles are stripped tidally as a substructure falls into a
host halo, the result will be a decrease in the spin. This implies
that a radial dependent factor needs to be taken into account when
compiling substructure catalogues, as the infalling haloes tend to
have their outer particles removed. Once the outer layer has been
lost the spin parameter generally increases to smaller radii as less
mass is considered.

The value of the spin parameter measured is dependent upon the
choice of where to place the outer edge and precisely which material
is included in the calculation. As we have shown here and
elsewhere these choices are very halo finder dependent and so care
should be taken when intercomparing spin parameter measurements
from different codes.
In a future project, we plan to look more closely at the difference between field and substructure haloes, to compare more directly the spin parameter found.

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REFERENCES

Springel V. et al., 2005, Nat, 435, 629

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