Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **424,** 502–507 (2012) doi:10.1111/j.1365-2966.2012.21219.x

The radius of baryonic collapse in disc galaxy formation

Susan A. Kassin,[1⋆†] Julien Devriendt,[2] S. Michael Fall,[3] Roelof S. de Jong,[4] Brandon Allgood[5‡] and Joel R. Primack[5]

[1]*Astrophysics Science Division, Goddard Space Flight Center, Code 665, Greenbelt, MD 20771, USA*
[2]*Sub-Department of Astrophysics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH*
[3]*Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA*
[4]*Astrophysikalisches Institut Potsdam (AIP), An der Sternwarte 16, 14482 Potsdam, Germany*
[5]*Department of Physics, University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95064, USA*

Accepted 2012 April 30. Received 2012 April 27; in original form 2012 February 1

ABSTRACT

In the standard picture of disc galaxy formation, baryons and dark matter receive the same tidal torques, and therefore approximately the same initial specific angular momentum. However, observations indicate that disc galaxies typically have only about half as much specific angular momentum as their dark matter haloes. We argue this does not necessarily imply that baryons lose this much specific angular momentum as they form galaxies. It may instead indicate that galaxies are most directly related to the inner regions of their host haloes, as may be expected in a scenario where baryons in the inner parts of haloes collapse first. A limiting case is examined under the idealized assumption of perfect angular momentum conservation. Namely, we determine the density contrast Δ, with respect to the critical density of the Universe, by which dark matter haloes need to be defined in order to have the same average specific angular momentum as the galaxies they host. Under the assumption that galaxies are related to haloes via their characteristic rotation velocities, the necessary Δ is $\sim$600. This Δ corresponds to an average halo radius and mass which are $\sim$60 per cent and $\sim$75 per cent, respectively, of the virial values (i.e. for $\Delta = 200$). We refer to this radius as the radius of baryonic collapse $R_{\rm BC}$, since if specific angular momentum is conserved perfectly, baryons would come from within it. It is not likely a simple step function due to the complex gastrophysics involved; therefore, we regard it as an effective radius. In summary, the difference between the predicted initial and the observed final specific angular momentum of galaxies, which is conventionally attributed solely to angular momentum loss, can more naturally be explained by a preference for collapse of baryons within $R_{\rm BC}$, with possibly some later angular momentum transfer.

Key words: galaxies: evolution – galaxies: formation – galaxies: fundamental parameters – galaxies: kinematics and dynamics.

1 INTRODUCTION

In the standard picture of disc galaxy formation (e.g. Fall & Efstathiou 1980; Dalcanton, Spergel & Summers 1997; Mo, Mao & White 1998), galaxies consist of a dissipative baryonic component and a non-dissipative dark matter component. Galaxies form hierarchically, and in this process, baryons and dark matter acquire the same specific angular momentum (j) via tidal torques. This is because tidal torques are most effective in the linear and the translinear regimes, when baryons and dark matter are well mixed. The dark matter then collapses non-dissipatively, and the baryons dissipatively, likely with some cloud–cloud collisions and possibly shocks (processes which are expected to rearrange j but not remove it). The baryons form rotating centrifugally supported discs at the centres of the potential wells. For a review of this scenario see Fall (2002). This standard picture is able to correctly predict galaxy properties such as scale-lengths and sizes if the baryons retain most of their initial j. It has been extended to include additional physics effects and larger samples of galaxies by e.g. White & Frenk (1991), Cole et al. (1994), Somerville & Primack (1999), de Jong & Lacey (2000), Van den Bosch (2001), Hatton et al. (2003) and Dutton (2009).

⋆E-mail: susan.kassin@nasa.gov
†NASA Postdoctoral Program Fellow.
‡Present address: Numerate Inc., 1150 Bayhill Drive, San Bruno, CA 94066, USA.

In order for this scenario to correctly predict galaxy properties, the baryons must retain a large fraction of their initial angular momentum. However, early numerical simulations of galaxy formation contradicted this expectation (Katz & Gunn 1991; Navarro & Benz 1991; Navarro & White 1994). They found a factor of ∼30 loss of angular momentum for simulated galaxies, and referred to this as an 'angular momentum catastrophe'. As simulations improved over the years, it became clear that much of this catastrophe was actually a numerical artefact: too little resolution and too much numerical viscosity (see e.g. Governato et al. 2010; Brook et al. 2011; Brooks et al. 2011; Kereš et al. 2011; Kimm et al. 2011, and references therein). Another possible contribution to solving the angular momentum problem may be through feedback effects which can delay baryons from falling on to discs (e.g. Weil, Eke & Efstathiou 1998; Sommer-Larsen, Gelato & Vedel 1999; Eke, Efstathiou & Wright 2000; Thacker & Couchman 2001). With high numerical resolution and some feedback, galaxy simulations are now at a stage where angular momentum loss may be a relatively minor problem. In this paper, we explore another option that the discs of galaxies draw baryons mainly from the inner parts of dark matter haloes. Some of the baryons in the outer parts may have not yet collapsed on to the discs.

The angular momentum catastrophe prompted comparisons of the j of simulated *haloes* to that of observed galaxies. In these studies, the j of dark matter haloes is measured out to the virial radius, $R_{\rm Vir}$, which is standardly defined as $R_{\Delta=200}$, and is the effective radius at which the dark matter ceases to collapse into the halo. Navarro & Steinmetz (2000) and Burkert & D'Onghia (2004) found that observed galaxies have 45 and 70 per cent of the j of their expected host haloes in simulations, respectively, under the assumptions that galaxies can be related to simulated host haloes via characteristic rotation velocities directly and via a scaling factor, respectively. Recently, Dutton & van den Bosch (2012) found that the spin parameters of observed galaxies are ∼60 per cent of those of simulated haloes. These studies are consistent once differences in assumptions and approximations are accounted for.

Studies which compare the total j predicted for haloes by numerical simulations to that observed for galaxies all assume that the effective outer halo radius from which the baryons collapse (defined here as $R_{\rm BC}$) is equal to $R_{\rm Vir}$. Because baryons in the inner parts of haloes will have higher cooling rates and more frequent cloud–cloud collisions, it is reasonable to expect that they form the galaxies, and that baryons from larger radii are not captured. Although $R_{\rm Vir}$ has traditionally been identified with $R_{\rm BC}$, these two radii are governed by different physics (dissipative versus non-dissipative), and need not be related, as emphasized by Fall (2002). The only requirement is that $R_{\rm BC}$ must be interior to $R_{\rm Vir}$, since baryons cannot collapse from unvirialized regions. The purpose of this paper is to determine the effect of relaxing the assumption that $R_{\rm Vir}$ and $R_{\rm BC}$ are equal on the difference in j between galaxies and haloes. We assume for simplicity that the boundary between the collapsed and uncollapsed baryons is a sharp one. In reality, it will be a gradual boundary because some of the baryons in the halo within $R_{\rm BC}$ might not collapse, and some baryons outside of $R_{\rm BC}$ might. Therefore, we regard $R_{\rm BC}$ as the effective boundary between these two regions.

In this paper, we ask the following question: if galaxies formed from all the baryons in haloes out to $R_{\rm BC}$, and beyond this radius the baryons remained in the halo, what is the value of $R_{\rm BC}$ required to match the j of galaxies? We address this question by comparing the j observed for disc galaxies with that of their expected dark matter haloes measured within a range of halo radii. For disc galaxies, j can be measured from observations of surface brightness profiles and rotation curves. For dark matter haloes, we must resort to numerical simulations.

This paper is organized as follows. In Section 2, we measure j of dark matter haloes in a cosmological dark matter-only simulation. We investigate its dependence on the halo radius within which j is measured and the halo radius at which the rotation velocity is measured. The resulting predictions of dark matter halo j are compared to j measured for a large observational sample of local galaxies for which the completeness is known in Section 3. A discussion of the results is in Section 4. We adopt a Λ cold dark matter (ΛCDM) concordance universe [$\Omega_{\rm m} = 0.24$, $\Omega_\Lambda = 0.76$, $h = H_0/(100\,{\rm km\,s^{-1}\,Mpc^{-1}}) = 0.73$, $\sigma_8 = 0.77$ and $n = 0.958$], i.e. within one standard deviation of both the 3-year *Wilkinson Microwave Anisotropy Probe* (*WMAP*3) and *WMAP*5 best estimates (Spergel et al. 2007; Dunkley et al. 2009). All logarithms are to the base 10.

2 *N*-BODY SIMULATION OF DARK MATTER HALOES

To quantify the dependence of dark matter halo j on how the outer radius of a halo is defined, we look to a suite of cosmological N-body simulations of dark matter haloes. These simulations include only dark matter and gravity (i.e. neither baryons nor hydrodynamics). As discussed in Section 1, if the baryons in a given dark matter halo are initially distributed in the same manner as the dark matter, and they later cool to form a disc while conserving j, then the j of the galaxy should be equal to that of the virialized region of the dark matter halo. However, if baryons collapse progressively from the inner parts to the outer parts of haloes, and they have not finished collapsing (or, if some baryons never collapse), then galaxy j may be expected to reflect that of dark matter haloes within a given radius, $R_{\rm BC}$.

To predict the distribution of j among dark matter haloes, a large N-body simulation is needed which can model the acquisition of angular momentum for even the slowest rotating galaxies in our sample (125 km s^{-1}; Section 3). The simulation we adopt is part of the Horizon Project suite (http://www.projet-horizon.fr). This follows the evolution of a cubic cosmological volume of 100 h^{-1} Mpc on a side (comoving) containing ∼134 million dark matter particles (512^3). It starts at $z = 99$ and is evolved using the publicly available tree code GADGET 2 (Springel 2005) with a softening length of 5 h^{-1} kpc (comoving). The adopted cosmology results in a dark matter particle mass of $6.83 \times 10^8\,{\rm M_\odot}$. Dark matter haloes and the subhaloes they contain are identified with the ADAPTAHOP algorithm (Aubert, Pichon & Colombi 2004). The halo centres are positioned on the densest dark matter particle located in the most massive substructure (see Tweed et al. 2009 for details). The total number of haloes and subhaloes in the simulation volume at $z = 0$ with more than 100 particles within R_{200} and with circular velocities at this radius which are greater than 100 km s^{-1} is 9661.

The j of a halo is measured within a range of radii as follows. First, the halo is divided into 100 radial ellipsoidal shells, where the axis ratios of the ellipsoid are obtained by computing the inertial tensor of all the particles in the halo. Halo circular radii are defined as the cube root of the radii of the three major axes of each ellipsoid. Next, the vector angular momentum of the particles in each shell is calculated, and the angular momenta of the shells are summed vectorially from the innermost shell to the radii specified before taking its modulus. The mass of a halo is measured in an analogous manner, and j is simply the angular momentum divided by the mass within a given radius. Selected radii, R_Δ, are defined by the density

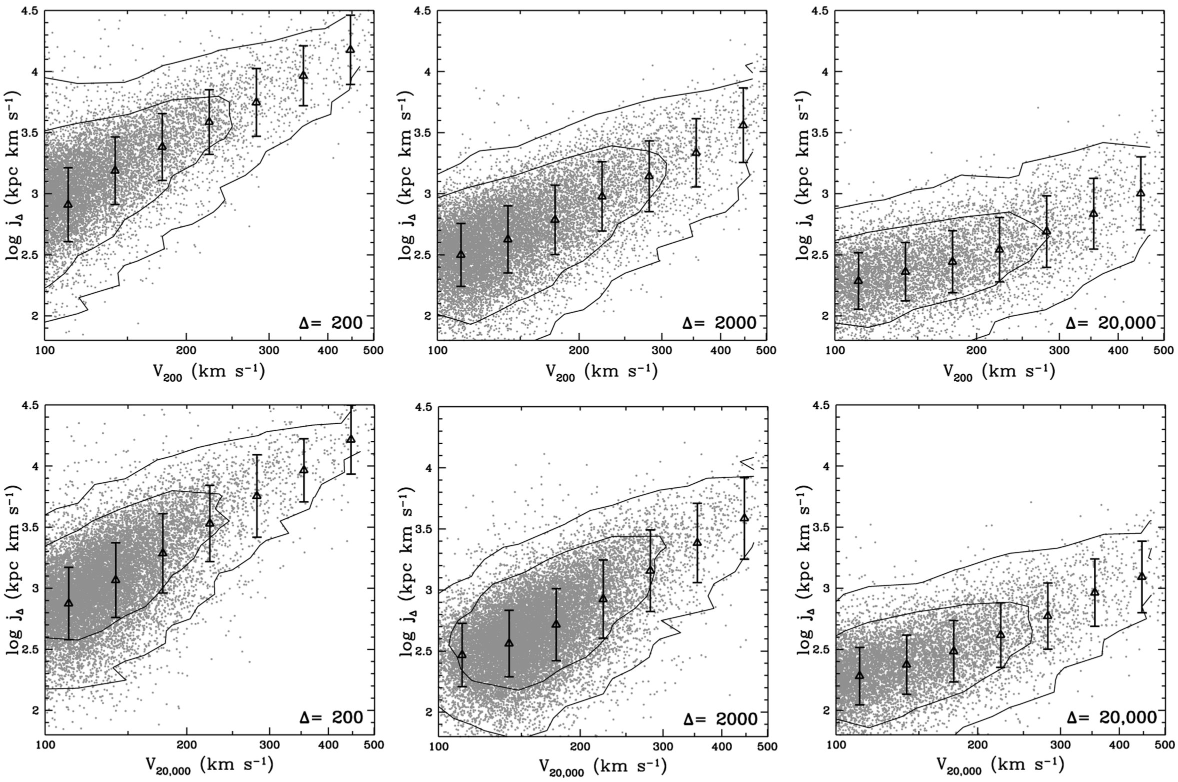

Figure 1. For simulated dark matter haloes at $z = 0$, the relations between j_Δ (for $\Delta = 200$, 2000 and 20 000) and rotation velocities V_{200} and $V_{20\,000}$ are shown. Individual haloes are plotted as grey points, binned averages are shown as black triangles and the rms scatter is shown as black error bars. Contours in volume density are shown for 2 and 20×10^{-5} haloes per 0.1 in log j_Δ and per 0.1 in log V per Mpc^3. The shapes of the distributions are similar for j_Δ whether V_{200} or $V_{20\,000}$ is adopted. As Δ increases, the normalization of the relation between j_Δ and V decreases, but the slope and scatter do not change greatly. Similar relations are found for V_{2000}, but are not shown to avoid redundancy.

of the haloes with respect to the critical density of the universe ($\Delta \equiv \bar{\rho}(r < R_\Delta)/\rho_{\rm crit}$). Specific angular momenta measured within these radii are defined as j_Δ. Circular velocities at these radii are $V_\Delta = (GM_\Delta/R_\Delta)^{1/2}$, where M_Δ and R_Δ are the mass and radius of the halo defined by Δ, and G is the gravitational constant. The ranges of Δ, R_Δ/R_{200} and M_Δ/M_{200} probed are 50–20 000, 1.70–0.09 and 1.24–0.13, respectively.

In Fig. 1, relations between halo j_Δ and V_Δ are shown.[1] Halo j is measured within R_{200}, R_{2000} and $R_{20\,000}$, and halo V is measured at R_{200} and $R_{20\,000}$. We do not show results for halo V measured at R_{2000} since they do not differ significantly from those for R_{200} or $R_{20\,000}$. The radii R_{2000} and $R_{20\,000}$ correspond to 34 and 9 per cent of R_{200}, respectively, on average. Only haloes with more than 100 particles are retained, except for measurements of $j_{20\,000}$ and $V_{20\,000}$ for which haloes with more than 50 particles are used. For these 50-particle haloes, the intrinsic relations remain the same, but the scatter is increased slightly due to increased Poisson noise. The shapes of all the distributions are similar in terms of slope and scatter, and are therefore approximately independent of the radius for which j or V is measured. The slope flattens slightly with increasing Δ, and the scatter remains about the same. We will quantify this in the following section. However, the normalization is strongly dependent on Δ: it decreases by factors of ∼3 and ∼6 for 10- and 100-fold increases in Δ, respectively. A decreasing normalization with increasing Δ is a consequence of how angular momentum is distributed in galactic haloes, with most of the angular momentum located in the outer parts. As we increase Δ, we exclude more and more of the outer parts of the haloes, and the angular momenta decrease, as illustrated by the simple analytic treatment in Fall (1983, Section 4). In this paper, we quantify this decrease more precisely using numerical simulations.

3 COMPARISON WITH OBSERVATIONS OF DISC GALAXIES

The goal of this section is to place measurements for disc galaxies in Fig. 1. To do so, we need to (1) adopt a galaxy sample for which the completeness is well defined and which has the necessary data available to derive circular velocities and j and (2) relate galaxies to simulated host dark matter haloes.

To address the first need, a large sample of 456 galaxies from Mathewson, Ford & Buchhorn (1992) and completeness measurements from de Jong & Lacey (2000) are adopted. Details of this sample are given below. The large size of and the data available for the sample necessitates simple estimates of j. Therefore, we estimate j as $2V_{\rm flat}r_{\rm d}$, where $V_{\rm flat}$ is the rotation velocity on the flat part of the rotation curve and $r_{\rm d}$ is the scale-length of the galaxy disc. This approximation is exact for an exponential disc and a flat rotation curve. Uncertainties in estimates of j are ∼15 per cent, which are dominated by errors in measurements of $r_{\rm s}$ (mainly due to errors

[1] There is a drawback to a plot of j versus V, namely both axes incorporate factors of V, and a relation is expected by construction (e.g. Freeman 1970). Because the local relation between galaxy V and stellar mass is tight (e.g. Bell & de Jong 2001; Kassin, de Jong & Weiner 2006), there is a similarly tight relation between between j and stellar mass (e.g. Fall 1983), which is not expected by construction.

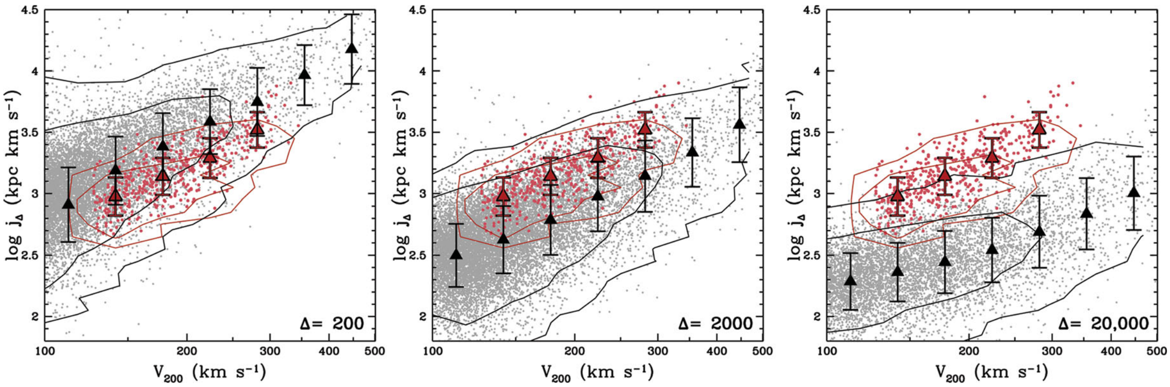

Figure 2. These plots are the same as in Fig. 1 for V_{200}, except here observed galaxies are also shown ($V_{\rm flat}$ of the galaxies is adopted as a characteristic rotation velocity and is plotted on the horizontal axis). Individual galaxies are plotted as red points, and contours in volume density are shown in red for 2 and 20×10^{-5} galaxies per 0.1 in log j_Δ and per 0.1 in log V_{200} per Mpc^3. Binned averages for the galaxies are shown as red triangles, and the rms scatter is denoted by error bars. The scatter in j for galaxies is about half of that of the haloes. Under the assumption that characteristic galaxy and halo rotation velocities are equal (i.e. $V_{\rm flat} = V_{200}$), galaxies have on average a factor of ∼2 less j than haloes defined with $\Delta = 200$, a factor of ∼2 more j than haloes defined with $\Delta = 2000$ and a factor of ∼5.6 more j than haloes defined with $\Delta = 20\,000$.

in sky background subtraction) and galaxy distances. There are two minor effects on estimates of j, which we do not take into account, but which work in opposite directions. On one hand, galaxies have rising rotation curves in their centres, and this causes the formula to slightly overestimate j. On the other hand, most galaxies are expected to have extended gas discs, but with very little mass, which would cause the formula to slightly underestimate j.

The galaxy sample used is a subsample of the European Southern Observatory (ESO)-Uppsala Catalogue of Galaxies (Lauberts 1982) which was selected by eye from photographic plates. It is only incomplete for very late Hubble types ($T > 6$, i.e. later than Scd; de Jong & Lacey 2000). Values of $V_{\rm flat}$ were determined from optical and radio observations. For the optical data, $V_{\rm flat}$ was defined as half the difference between the maximum and minimum velocities of the Hα rotation curves. For the radio data, $V_{\rm flat}$ was defined as half the width of the H I profile between points where the intensity falls to 50 per cent of the highest values; these values were then corrected for dispersion and converted to optical rotation velocities by multiplying by 1.03 and then subtracting 11 km s^{-1} (see section 3.4 and fig. 5 of Mathewson et al. 1992). Disc half-light radii, which are the result of I-band bulge–disc decompositions from de Jong & Lacey (2000), are converted to disc scale-lengths by dividing by 1.679 (the exact ratio of the half-mass radius to the scale radius for a pure exponential disc). Only those galaxies with rotation velocities greater than 125 km s^{-1} are used. This helps us to avoid galaxies with rotation curves which do not flatten out at the radii measured. The distribution of galaxies in j versus $V_{\rm flat}$ does not differ significantly from the galaxy sample commonly used in the literature (Courteau et al. 2007), but it has a better completeness.

To address the second need, and relate galaxies to the dark matter haloes in Fig. 1, we assume for simplicity that the characteristic rotation velocity of a galaxy (which we take to be $V_{\rm flat}$) and that of its host halo at R_{200} are equal. For a massless disc in a Navarro, Frenk & White (1996) halo, V_c at the location of the galaxy can be about half its value at R_{200}. However, the self-gravity of the baryons is expected to increase V_c in the inner parts of haloes. The amount by which it increases is difficult to calculate theoretically, so we look to observations. Dutton et al. (2010) finds a very small conversion factor between V_c at R_{200} and at the location of galaxy discs. In their analysis, Dutton et al. (2010) combined dark halo masses measured from satellite kinematics and weak gravitational lensing to show that $V_{2.2} \simeq V_{200}$ for $V_{2.2} = 90$–260 km s^{-1}, where $V_{2.2}$ is the galaxy rotation velocity measured at 2.2 I-band scale-lengths. This equivalence is also consistent with semi-analytic models of galaxy formation which require a similar ratio between galaxy and halo velocities to simultaneously match the local Tully–Fisher relation and galaxy luminosity function (e.g. Dutton & van den Bosch 2009, and references therein).

In Fig. 2, we compare the distribution of j versus $V_{\rm flat}$ for galaxies described in this section with the distributions of j_{200}, j_{2000} and $j_{20\,000}$ versus V_{200} for dark matter haloes from Fig. 1. As discussed above, it is assumed that haloes have the same rotation velocities as the galaxies they host, so they can be directly compared in Fig. 2. The halo relations from Fig. 1 for $V_{20\,000}$ are not shown because they are not significantly different from those for V_{200}. We fit a linear relation to the galaxies using 100 bootstrap resamplings and a generalized least-squares fitting routine (Weiner et al. 2006), which gives a slope of 2.5 ± 0.1 rms. We also fit a linear relation to the haloes in Fig. 2 for j_{200} versus V_{200} for circular velocities which span the velocity range of the galaxies, $125 < V_{200} < 315$ km s^{-1}. This results in a slope of 1.92 ± 0.02 rms. The distribution of galaxies has a similar slope to that of the haloes, as found by Fall (1983) and others (e.g. Mo et al. 1998; Navarro & Steinmetz 2000), and approximately half the average rms scatter (0.15 dex versus 0.27 dex). The lower scatter compared to the haloes is related to the finding by de Jong & Lacey (2000) that the width of the observed scale-radius distribution of galactic discs is narrower than that expected from the distributions of halo spin parameters in cosmological simulations. For the halo j_{2000} versus V_{200} and $j_{20\,000}$ versus V_{200} relations, the slopes are 1.80 ± 0.02 and 1.26 ± 0.02, respectively, and the average rms scatters are 0.28 and 0.26, respectively. The slopes flatten slightly with increasing Δ, but the scatter remains constant to within errors. Given all the factors not included in our simple picture, we consider it remarkable how similar the galaxy and halo slopes are. The main result of this paper is encapsulated in the much larger difference in normalization between galaxies and haloes. We choose to measure this difference at approximately the centre of the distributions, at $\log V_{\rm rot} = 2.35$ ($V_{\rm rot} = 224$ km s^{-1}). The average normalization of the galaxies is less than that of the haloes for j_{200} by a factor of ∼2 (0.30 dex), consistent with previous studies (e.g. Navarro

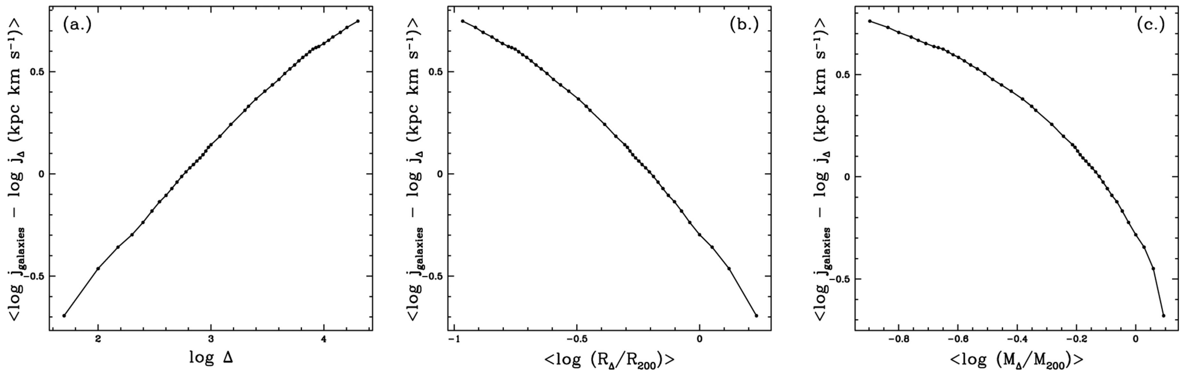

Figure 3. The average difference between galaxy and halo log j, $\langle \log j_{\rm galaxies} - \log j_{\Delta} \rangle$, is shown as a function of Δ, R_{Δ}/R_{200} and M_{Δ}/M_{200}, in panels (a), (b) and (c), respectively. Points demarcate discreet values, and solid lines simply connect the points. There is no offset between galaxy and halo log j for $\Delta = 578^{+34}_{-31}$, which corresponds to $R_{\rm BC} = R_{\Delta=578}/R_{200} = 0.63^{+0.02}_{-0.01}$, and $M_{\Delta\ =578}/M_{200} = 0.74 \pm 0.1$.

& Steinmetz 2000; Dutton & van den Bosch 2012). The average normalization of the galaxies is greater than that of the haloes for j_{2000} and $j_{20\,000}$ by factors of ∼2 (0.30 dex) and ∼5.6 (0.75 dex), respectively.

We quantify the dependence of j_{Δ} on Δ as follows. We start by measuring halo j for a range of Δ and compare them with j measured for the galaxy sample, as in Fig. 2. In Fig. 3, we show the average difference between galaxy and halo j (measured at log $V_{\rm rot} = 2.35$) as a function of Δ, halo outer radius in terms of R_{200} (i.e. R_{Δ}/R_{200}) and halo mass in terms of M_{200} (i.e. M_{Δ}/M_{200}). The quantities R_{Δ}/R_{200} and M_{Δ}/M_{200} are average values for all haloes with circular velocities which span $125 < V_{200} < 315\,{\rm km\,s^{-1}}$. The value of Δ at which the average j of galaxies and haloes match (i.e. $\langle \log j_{\rm galaxies} - \log j_{\Delta} \rangle = 0$) is 578^{+34}_{-31}. The halo j_{578} versus V_{200} relation has a slope of 1.89 ± 0.03 and an average rms scatter of 0.28 dex over the velocity range of the galaxies. This value of Δ corresponds to $R_{\rm BC} = R_{\Delta=578}/R_{200} = 0.63^{+0.2}_{-0.1}$ and $M_{\Delta=578}/M_{200} = 0.74 \pm 0.1$. We calculate these values by interpolating the curves in Fig. 3, and the errors by considering the limiting case that galaxy j values are systematically overestimated and underestimated by the assumed measurement uncertainty. If baryons conserved j perfectly during galaxy formation, then the collapse radius $R_{\rm BC}$ is $\simeq 63$ per cent of the virial radius R_{200}. This portion of the haloes contains on average 74 per cent of their mass, and if baryons and dark matter are initially well mixed, the same percentage of the baryons. However, as discussed in the next section, this radius and mass fraction are probably not simple step functions; therefore, we regard them as ‘effective’ quantities.

4 DISCUSSION

In this paper, we determine the extent to which the approximate factor of 2 discrepancy between the j of galaxies and their expected host dark matter haloes is sensitive to the conventional assumption that $R_{\rm BC} = R_{200}$. This difference in j is usually attributed to loss of baryonic j during galaxy formation. However, there is no physical reason for the assumption that these radii are equal to at least within a factor of ∼2, as emphasized by Fall (2002). This is because different physics governs each, namely dissipational and dissipationless physics for $R_{\rm BC}$ and $R_{\rm Vir}$, respectively. The only constraint on the relationship between these radii is that $R_{\rm BC}$ must be interior to $R_{\rm Vir}$ since baryons cannot collapse from a region that is not incorporated into the halo. A $R_{\rm BC}$ which is interior to $R_{\rm Vir}$ is a natural expectation in the standard theory of galaxy formation where the inner parts of haloes collapse first. As $R_{\rm BC}$ decreases, the discrepancy between the j of galaxies and haloes is alleviated. We show that the discrepancy can be explained entirely by a $R_{\rm BC}$ which is ∼60 per cent of $R_{\rm Vir}$.

To do so, we determine the value of $R_{\rm BC}$ at which the j of galaxies and haloes match. This is done by comparing the distribution of j observed for a sample of local disc galaxies, for which the completeness is understood, to that predicted for their host dark matter haloes from a dark matter-only simulation of the Universe. It is assumed that galaxies and haloes can be related directly via their rotation velocities. The necessary value of the density contrast Δ needed to define the haloes which have the same average j as galaxies is ∼600. This corresponds to an average effective $R_{\rm BC}$ which is ∼60 per cent of R_{200}, and an average halo mass which is ∼75 per cent of M_{200}. Therefore, if galaxies formed from baryons initially present in the inner parts of their host haloes and conserved j perfectly, the baryons would come from within $R_{\rm BC}$ and would comprise this percentage of the baryons in the halo.

Even under the assumption of perfect conservation of j, $R_{\rm BC}$ is not likely a sharp boundary. The baryons which form the galaxy may only on average come from within $R_{\rm BC}$, with most material originating from smaller radii, but some from more distant radii. In addition, the smaller scatter of the galaxies in j versus V compared to that of the haloes may indicate a mechanism by which only selected baryons form the disc, regulatory processes which act upon the baryons, and/or haloes which form non-disc galaxies. This is because, in our simple picture, the initial distribution of baryons in j versus V is expected to mirror that of the dark matter. Therefore, if only selected baryons formed discs or regulatory processes acted upon them during disc formation, it may be expected that the baryons which form the discs would have a narrower distribution in j versus V. In addition, since we compare the predicted properties of dark matter haloes with those of disc galaxies, not ellipticals which rotate slower than discs, it stands to reason that the combined population of discs and ellipticals would be broader in j versus V (Fall 1983).

Eventually, it should be possible to compute $R_{\rm BC}$ from hydrodynamical and dark matter simulations of galaxy formation in a cosmological context. Current simulations may have spatial and mass resolutions that are too coarse to model accurately the complex processes expected to be at play, such as gas shocks, cloud–cloud collisions and a multiphase medium. These processes affect the rate at which the baryons collapse, but they may have relatively little influence on the angular momentum of the resulting galactic discs.

A number of phenomena can alter the j of galaxies [see Fall 2002 and Romanowsky & Fall (in preparation) for more complete discussions of these phenomena]. For example, torques exerted between the dark matter and the baryons could in principle spin up the halo and spin down the disc. Minor mergers might also affect the j of galaxies. In addition, feedback from star formation can alter j differently depending on how it varies with radius. Material in outflows may be launched from inner or outer radii, or both. If material is primarily removed from the inner or outer parts of galaxies, galaxy j will increase or decrease, respectively. If feedback is active but independent of radius, then there would be no change in j. We expect some of these phenomena to alter the j of discs, but whether they have a major or a minor effect on galaxy j is still uncertain. In order to perform a more detailed comparison of galaxies and haloes, we need a better understanding of the processes of j transfer in galaxy formation, and whether outflows can change the j of galaxies.

In summary, the difference between the predicted initial and the observed final j of galaxies, which is conventionally attributed solely to angular momentum loss, hinges on the loosely motivated assumption that all the baryons within $R_{\rm Vir}$ collapse to form galaxies. There is no physical reason why this has to be the case. If baryons in the inner parts of haloes collapse first, as is expected, then the j discrepancy between galaxies and haloes can be fully explained by a collapse radius $R_{\rm BC}$ which is ∼60 per cent of the virial radius $R_{\rm Vir}$. In the future, baryons from progressively larger radii in the halo may collapse, and at some point in time $R_{\rm BC}$ might equal $R_{\rm Vir}$. In reality, it may be that a combination of a preference of collapse of the inner parts and some j transfer between baryons and dark matter is needed to solve the problem.

ACKNOWLEDGMENTS

This research was supported by an appointment to the NASA Postdoctoral Program at NASA's Goddard Space Flight Center, administered by Oak Ridge Associated Universities through a contract with NASA. The research of JD is partly supported by Adrian Beecroft, the Oxford Martin School and STFC. This work was performed using code and simulations from the Horizon collaboration (http://www.projet-horizon.fr). SAK and JD are grateful to David S. Graff. We thank Aaron Dutton and Aaron Romanowski for helpful comments on drafts of this paper.

REFERENCES

Aubert D., Pichon C., Colombi S., 2004, MNRAS, 352, 376
Bell E. F., de Jong R. S., 2001, ApJ, 550, 212
Brook C. et al., 2011, MNRAS, 415, 1051
Brooks A. et al., 2011, ApJ, 728, 51
Burkert A., D'Onghia E., 2004, in Block D., Puerari I., Freeman K., Groess R., Block E., eds, Penetrating Bars Through Masks of Cosmic Dust. Springer-Verlag, Berlin, p. 341
Cole S., Aragon-Salamanca A., Frenk C. S., Navarro J. F., Zepf S. E., 1994, MNRAS, 271, 781
Courteau S., McDonald M., Widrow L. M., Holtzman J., 2007, ApJ, 655, L21
Dalcanton J. J., Spergel D. N., Summers F. J., 1997, ApJ, 482, 659
de Jong R. S., Lacey C., 2000, ApJ, 545, 781
Dunkley J. et al., 2009, ApJS, 180, 306
Dutton A. A., 2009, MNRAS, 396, 121
Dutton A. A., van den Bosch F. C., 2009, MNRAS, 396, 141
Dutton A. A., van den Bosch F. C., 2012, MNRAS, 421, 608
Dutton A. A., Conroy C., van den Bosch F. C., Prada F., More S., 2010, MNRAS, 407, 2
Eke V., Efstathiou G., Wright L., 2000, MNRAS, 315, 18
Fall S. M., 1983, in Athanassoula E., ed., Internal Kinematics and Dynamics of Galaxies. Reidel, Dordrecht, p. 391
Fall S. M., 2002, in Athanassoula E., Bosma A., Mujica R., eds, ASP Conf. Ser. Vol. 275, Discs of Galaxies: Kinematics, Dynamics and Perturbations. Astron. Soc. Pac., San Francisco, p. 389
Fall S. M., Efstathiou G., 1980, MNRAS, 193, 189
Freeman K. C., 1970, ApJ, 160, 811
Governato F. et al., 2010, Nat, 463, 203
Hatton S., Devriendt J. E. G., Ninin S., Bouchet F. R., Guiderdoni B., Vibert D., 2003, MNRAS, 343, 75
Kassin S. A., de Jong R. S., Weiner B. J., 2006, ApJ, 643, 804
Katz N., Gunn J. E., 1991, ApJ, 377, 365
Kereš D., Vogelsberger M., Sijacki D., Springel V., Hernquist L., 2011, preprint (arXiv:1109.4638)
Kimm T., Devriendt J., Slyz A., Pichon C., Kassin S. A., Dubois Y., 2011, preprint (arXiv:1106.0538)
Lauberts A., 1982, The ESO-Uppsala Survey of the ESO (B) Atlas. European Southern Observatory, Garching
Mathewson D. S., Ford V. L., Buchhorn M., 1992, MNRAS, 81, 413
Mo H. J., Mao S., White S. D. M., 1998, MNRAS, 295, 319
Navarro J. F., Benz W., 1991, ApJ, 380, 320
Navarro J. F., Steinmetz M., 2000, ApJ, 538, 477
Navarro J. F., White S. D. M., 1994, MNRAS, 267, 401
Navarro J. F., Frenk C. S., White S. D. M., 1996, ApJ, 462, 563
Somerville R. S., Primack J. R., 1999, MNRAS, 310, 1087
Sommer-Larsen J., Gelato S., Vedel H., 1999, ApJ, 519, 501
Spergel D. N. et al., 2007, ApJS, 170, 377
Springel V., 2005, MNRAS, 364, 1105
Thacker R. J., Couchman H. M. P., 2001, ApJ, 555, 17
Tweed D., Devriendt J., Blaizot J., Colombi S., Slyz A., 2009, A&A, 506, 647
van den Bosch F. C., 2001, MNRAS, 327, 1334
Weil M. L., Eke V. R., Efstathiou G., 1998, MNRAS, 300, 773
Weiner B. J. et al., 2006, ApJ, 653, 1049
White S. D. M., Frenk C. S., 1991, ApJ, 379, 52

This paper has been typeset from a TEX/LATEX file prepared by the author.