Resolving the Spin Crisis: Mergers and Feedback

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Abstract. We model in simple terms the angular momentum \(J\) problem of galaxy formation in CDM, and identify the key elements of a scenario that can solve it. The buildup of \(J\) is modeled via dynamical friction and tidal stripping in mergers. This reveals how over-cooling in incoming halos leads to transfer of \(J\) from baryons to dark matter (DM), in conflict with observations. By incorporating a simple recipe of supernova feedback, we match the observed \(J\) distribution in disks. Gas removal from small incoming halos, which make the low-\(J\) component of the product, eliminates the low-\(J\) baryons. Partial heating and puffing-up of the gas in larger incoming halos, combined with tidal stripping, reduces the \(J\) loss of baryons. This implies a higher baryonic spin for lower mass halos. The observed low baryonic fraction in dwarf galaxies is used to calibrate the characteristic velocity associated with supernova feedback, yielding \(V_{fb} \sim 100\,\text{km}\,\text{s}^{-1}\), within the range of theoretical expectations. The model then reproduces the observed distribution of spin parameter among dwarf and bright galaxies, as well as the \(J\) distribution inside these galaxies. This suggests that the model captures the main features of a full scenario for resolving the spin crisis.

1 Introduction

The ‘standard’ model of cosmology, CDM, which assumes hierarchical buildup of structure, is facing difficulties in explaining observed properties of galaxies, such as the number density of dwarfs and the inner density profile of halos. Standing out is the angular-momentum problem, that is the apparent failure of the theory, via simulations, to reproduce the large sizes of disk galaxies and their structure. We make progress by first reproducing the problem via a simple model in which the important physical elements are spelled out, and then incorporating in this model the key process which may cure the problem — feedback.

The sizes of disks are commonly linked to the spins of their parent halos as measured in N-body simulations [10]. The assumptions that the baryons and DM share the same distribution of specific angular momentum \(j\) and that the baryons conserve their \(j\) while contracting to a disk lead to disk sizes comparable to those observed. However, simulations that incorporate gas find that most of the baryonic \(j\) is transfered to the DM, resulting in disk sizes smaller by an order of magnitude [e.g. 14,15], and thus leading to a spin catastrophe.

In addition, there is a mismatch of \(j\) profiles. The \(j\) distribution (or profile) within simulated halos has been found to scatter about a universal shape, with an excess of low-\(j\) (and high-\(j\)) material compared to the exponential disks observed [1, BD]. This mismatch has been demonstrated in an observed sample of
14 dwarf galaxies [18, BBS], which serves as the target for our modeling effort. BBS used for each halo the measured rotation curve and an assumed NFW profile to determine the halo virial quantities, with an average $\langle V_{\text{vir}} \rangle \approx 60 \text{ km s}^{-1}$. They then determined the baryonic spin parameter, averaging to $\langle \lambda'_b \rangle \sim 0.07$, significantly larger than the $\langle \lambda'_{\text{dm}} \rangle \sim 0.035$ of simulated halos, and then demonstrated the $j$-profile mismatch case by case. BBS also estimated the ratio of disk to DM mass to be $\langle f_d \rangle \sim 0.04$, about a factor of 3 smaller than the universal fraction, indicating significant gas loss.

The spin catastrophe is commonly being associated with “over-cooling”, that the gas rapidly cools and becomes tightly bound in small halos. When such a halo spirals into a bigger halo, the baryonic component survives intact all the way to the center and thus transfers all its orbital $j$ to the DM. It has therefore been speculated that energy feedback from supernova may remedy the problem by balancing the early cooling [e.g. 9]. A key idea is that the spin segregation between baryons and DM can go either way. While gas cooling tends to lower the baryonic spin, heating due to feedback would reduce this effect, and gas removal from small halos would even lead to higher baryonic spin. However, a realistic implementation of feedback has proved challenging [e.g. 17]. The feedback process has not yet been studied or implemented in satisfactory detail. We do not know yet whether they can indeed solve the CDM problems, and how. This motivates our attempt to first understand how the feedback scenario may work using a very simple semi-analytic model. Knowing that in a hierarchical scenario the halo fromation can be largely interpreted as a sequence of mergers, our model is based on a simple algorithm for the buildup of halo spin by adding up the orbital angular momenta of merging satellites [13, MDS, 19]. It matches well the spin distribution among halos in N-body simulations as well as the $j$ profile within halos. This makes it a useful tool for understanding the over-cooling origin of the spin problem and for the attempt to cure it via feedback effects. Our work is described in more detail in [12, MD].

## 2 Buildup of Halo Spin by Mergers

We characterize the angular momentum $J$ of a galaxy by the modified spin parameter $\lambda = (J/M)/(\sqrt{2}V_{\text{vir}}R_{\text{vir}})$. This quantity, which equals the standard $\lambda$ for an isothermal sphere and for an NFW profile with concentration $c \sim 5$, is straightforward to compute separately for the baryons and for the DM, $\lambda'_b$ and $\lambda'_{\text{dm}}$. The distribution of $\ln \lambda'$ in the simulations is normal, with an average corresponding to $\lambda'_0 \approx 0.035$ (compared to $\lambda_0 \approx 0.042$) and a standard deviation $\sigma_{\lambda'} \approx 0.5$. The “orbital-merger” model of MDS reproduces this spin distribution. To materialize this model we generate many random realizations of merger histories based on the Extended Press Schechter formalism [11] with slight adjustments, and for each merger tree we create random realizations of the orbital $J$ added in each merger. The encounter parameters are taken to mimic typical mergers, with the directions of the orbits drawn at random (or fine-tuned for a slight correlation between successive mergers as seen in simulations [5,16].
The resultant distribution of halo spins matches the log-normal distribution obtained in the simulations.

The cumulative mass distribution of $j$ within simulated halos is fit by the universal function $M(< j) = M_0 \mu j / (j_0 + j)$, with $\mu > 1$ and $j \leq j_{\text{max}} = j_0 / (\mu - 1)$ (BD). This is a simple power law, $M(< j) \propto j$, for at least half the mass, with a possible bend characterized by $\mu$. The other parameter, $j_0$ or $j_{\text{max}}$, can be replaced by $\lambda'$. The distribution of $\mu$ is Gaussian in $\ln(\mu - 1)$, with a mean $-0.6$. The model also recovers these simulated $j$ profiles. We create an $M(< j)$ profile for each of the EPS model realizations by dividing the mass growth of the halo into bins and assigning to each the corresponding orbital $J$.

A sample of profiles produced by this procedure and the distribution of $\mu$ values are shown in Figs. 1 and 2 of MD, demonstrating the match with the simulation results of BD. The model also reproduces the insensitivity to halo mass and redshift.

The successes of the simple model in recovering both the distribution of spins and the $j$ profiles makes it a useful tool for studying the $j$ buildup. A new feature revealed by the model, which provides an interesting clue, is that the final halo spin is predominantly determined by the last major merger, while the many smaller satellites come in at different directions and therefore tend to sum up to a low $j$. If small satellites would lose gas before they merge into the halo, then much of the galactic gas would originate in big satellites, the final gas would lack the low-$j$ component, and the baryonic spin would end up higher than the DM.

### 3 Reproducing the Baryonic Spin Loss

We can understand the $j$ loss of baryons via a simple model including gas cooling, dynamical friction and tidal stripping for how the orbital $j$ is converted into halo spin. First, the dynamical friction exerted by the halo on the satellite brings the satellite towards the halo center and thus transfers $j$ from the orbit to the halo. Second, once satellite particles are tidally stripped they retain their $j$ at the stripping point and add it directly to the halo.

The mass loss at halo radius $r$ can be estimated by evaluating the tidal radius $\ell_\text{t}$ of the satellite at $r$ via the resonance condition, $m(\ell_\text{t})/\ell_\text{t}^3 = M(r)/r^3$, where $m(\ell)$ and $M(r)$ are the mass profiles of the satellite and halo. If these two are self-similar, then this implies $\ell_\text{t}/\ell_\text{vir} = r/R_\text{vir}$, and the bound mass of the satellite is $m[\ell_\text{t}(r)] \propto M(r)$. A more accurate recipe for tidal stripping, tested with merger simulations, reveals that this is a good approximation in general [6], so we adopt it in our model.

When exploring the effect of cooling, one assumes that initially the baryons follow the DM. As the gas cools, it contracts to a more compact configuration of radius $R_b < R_\text{dm}$. This spatial segregation in the satellite implies that the $j$-rich mass stripped at the early stages of the merger in the outer halo is dominated by DM, while the more compact baryons penetrate into the inner halo and lose more of their $j$ via dynamical friction. The result is a net spin transfer from the baryons to the DM. Using the stripping recipe $m(r) \propto M(r)$, we obtain for the
final baryonic spin \( J_b/J_{dm} = (R_b/R_{dm}) \). In the case of maximum cooling, the baryons dominate the halo center, \( R_b = f_b R_{dm} \), where \( f_b \approx 0.13 \) is the universal baryon fraction. Fig. 1 shows the resultant baryonic spin distribution according to this model; there is a shift down to \( \lambda'_0 = 0.005 \), reproducing the spin crisis. The role of feedback would be to delay the cooling, increase \( R_b \), and thus reduce the baryonic spin loss.

**Over-Cooling**

- \( \lambda'_0 = 0.005 \)
- \( \sigma_\lambda = 0.51 \)
- \( \lambda'_0 = 0.036 \)
- \( \sigma_\lambda = 0.53 \)

**Feedback**

- \( \lambda'_0 = 0.040 \)
- \( \sigma_\lambda = 0.43 \)
- \( \lambda'_0 = 0.068 \)
- \( \sigma_\lambda = 0.61 \)

**Fig. 1.** The effects of over-cooling and feedback on the spin distribution of baryons compared to the DM, for dwarf and bright galaxies. Log-normal fits are shown, with the mean and scatter quoted. **Left:** \( \lambda'_0 \) is shifted down by an order of magnitude compared to \( \lambda'_{dm} \), reproducing the spin catastrophe. **Right:** \( \lambda'_0 \) in bright galaxies is boosted up by heating and partial blowout in incoming halos and roughly matches \( \lambda'_{dm} \), while in dwarf galaxies \( \lambda'_0 \) is boosted up further by the blowout in small satellites.

## 4 Feedback

Our approach here is to avoid the details of star formation and feedback and rather appeal to a very simple prescription for the effect of feedback as a function of the satellite’s virial velocity, \( V_{sat} \). Following the analysis of Dekel & Silk [8], we assume that the feedback by supernova-driven winds pumps energy into the gas and heats it uniformly to a temperature corresponding to a characteristic velocity \( V_{fb} \), on the order of 100 km s\(^{-1}\). We therefore assume that the spatial extent of the baryons is determined by the ratio \( V_{fb}/V_{sat} \). The limit \( V_{sat} \gg V_{fb} \), of massive, deep potential wells, corresponds to maximum cooling, \( R_b \ll R_{dm} \). In smaller halos, Still with \( V_{sat} \approx V_{fb} \), we expect the heating to balance the cooling and yield \( R_b \approx R_{dm} \). Our model is therefore an interpolation between these limits, \( R_b = (V_{fb}/V_{sat})^{\gamma_1} R_{dm} \), with \( \gamma_1 \) an arbitrary exponent, which we set for now to be unity.

If \( V_{fb} \) is larger than \( V_{sat} \), the feedback can cause gas blowout. We assume that partial blowout starts occurring once \( V_{fb} \) exceeds the escape velocity of the satellite, \( \sim \sqrt{2} V_{sat} \), while total blowout is expected for \( V_{fb} \gg V_{sat} \). We therefore parameterize the amount of gas that remains in the halo by another
interpolation, \( f_d = (V_{fb}/V_{sat}/\sqrt{2})^{\gamma_2} \), with \( \gamma_2 \) an arbitrary exponent tentatively set to unity. We report here the results for the simplest choice \( \gamma_1 = \gamma_2 = 1 \), and explore the robustness of the results to different choices of \( \gamma_1 \) and \( \gamma_2 \) in MD.

In Fig. 1 we demonstrate the effects of this feedback scheme, with \( V_{fb} = 95 \text{ km s}^{-1} \), on the distribution of \( \lambda'_b \). We do it for two kinds of final halos, with \( V_{vir} = 60 \) and 220 km s\(^{-1} \), representing dwarf and bright galaxies. The baryons in the bright galaxies end up with spins comparable to their DM halos, with \( \lambda'_0 = 0.042 \), while in dwarfs they have significantly higher spins, with \( \lambda'_0 = 0.067 \). We learn that \( \lambda'_b \) in dwarfs, which are built up by small satellites, is dominated by the blowout from these satellites, and it ends up with \( \lambda'_b > \lambda'_{dm} \). For bigger galaxies, which are largely made of bigger satellites, the dominant effect is the heating, with some contribution from blowout, together leading to a \( \lambda'_b \) distribution similar to \( \lambda'_{dm} \), in general agreement with observations.

In MD we explore a range of values for the exponents \( \gamma_1 \) and \( \gamma_2 \). For each choice we determine \( V_{fb} \) such that for the dwarfs \( \langle f_d \rangle = 0.04 \) as in BBS. We find that our results for dwarfs remain practically unchanged, while the results for bright galaxies have a weak dependence on the value of \( \gamma_1 \) in the range (0.5, 3).

5 Model versus Observations

![Fig. 2.](image) Model realizations (with \( V_{fb} = 95 \text{ km s}^{-1} \)) versus BBS observations of dwarf galaxies (shaded). Distribution of baryon fraction \( f_d \), spin parameter \( \lambda' \), and \( j \)-profile shape parameter \( \zeta \). **Left:** The model prediction for \( V_{vir} = 60 \text{ km s}^{-1} \) dwarfs, with significant blowout, is in agreement with the BBS data, while the bright galaxies retain most of their baryons. **Middle:** The predicted \( \lambda'_b \) distribution is in agreement with the dwarf data. Shown for comparison is the simulation result for dark halos, which is similar to that of bright galaxies. **Right:** The predicted distribution of \( \zeta \) for the baryons in dwarfs (heavy histogram) is shifted upwards compared to the DM (smooth curve) and the bright galaxies (light histogram), like the data, but its width is overestimated.

The distribution of \( f_d \) for the dwarfs observed by BBS is displayed in Fig. 3, showing values significantly lower than the universal value of \( f_b \simeq 0.13 \) and thus consistent with baryonic blowout. Shown for comparison are the model predictions for dwarf and bright galaxies. We enforced a match of the means for the dwarfs at \( \langle f_d \rangle = 0.04 \) by choosing \( V_{fb} = 95 \text{ km s}^{-1} \), but the scatters are also in agreement. For bright galaxies, \( f_d \) is typically lower than the universal value.
by less than 50%, reflecting the limited fraction of small progenitors who lost their gas.

Next, we compare predicted and observed spin distributions for dwarfs. We convert each value of $\lambda$ as quoted by BBS to $\lambda'$, and show their distribution in Fig. 2. The observed spins are significantly higher than the $\lambda'$ values of halos in cosmological simulations, with an average of $\lambda'_0 \simeq 0.07$ compared to 0.035. Then shown is our model prediction with $V_{fb} = 95$ km s$^{-1}$ for the baryonic spin distribution in dwarfs. The effect of blowout brings the baryonic spins to a good agreement with the observed dwarfs.

Fig. 3 shows the average $j$ profiles and the scatter about them for the observed BBS dwarfs and for the corresponding model realizations compared to the typical $j$ profile in halos by BD. We construct the baryonic $j$ profile in each of our model realizations following the same method used to produce DM $j$ profiles but now including feedback effects. The BBS dwarfs show low baryonic fractions (indicated by the integral under the histogram) and significant deficits of $j$ at the two ends of the distribution compared to the halos. The profile for model dwarf galaxies is similar to the observations except for the very lowest $j$ bin which is a 2$\sigma$ overestimate, representing a spike in some of the model realizations. This spike may correspond to a low-$j$ baryonic component that BBS fail to observe (faint halo stars?), or the spiky objects do not become disk dwarf galaxies, or our model needs to be improved. The high-$j$ tail tends to be reduced in the baryons because it is often the result of a small satellite that comes in with its orbital $J$ aligned with the halo spin, and now has lost its gas.

![Fig. 3. Average $j$ profiles (histogram) and the 1$\sigma$ scatter (shaded) for the observed dwarfs in comparison with the model dwarf and bright galaxies ($V_{fb} = 95$ km s$^{-1}$). The integral under the histogram is $f_d$. Shown in comparison is the typical profile for DM halos by BD.](image)

Fig. 3 also shows the average model prediction for bright galaxies, $V_{vir} = 220$ km s$^{-1}$. They retain most of their baryons, so their profiles are less affected by blowout. The average model profile is in better agreement with an exponential disk, towards solving the $j$-profile discrepancy pointed out by BD.
A quantity used by BBS to characterize the shape of the $j$ profile, as an alternative to the BD parameter $\mu$, is $\zeta \equiv j_{\text{tot}}/j_{\text{max}}$. In Fig. 2 we also plot the distribution of this quantity in the BBS dataset in comparison with our model predictions for the baryons in dwarf and bright galaxies. The predicted $\zeta$ distribution for dwarfs is shifted upwards compared to the halos and the bright galaxies, in qualitative agreement with the BBS data, but the width is overestimated.

6 Conclusion

We devised a simple model to address the $j$ problems of galaxy formation within CDM. By adding up the orbital $J$ in random realizations of merger histories, the model successfully reproduces the simulated distribution of spins among halos (MDS) and the distribution of $j$ within halos (MD). A simple analysis of how the merger orbital $J$ turns into a spin profile provides a clue for how feedback effects in the satellite can resolve the spin problems. The idea is that the effective size of the gas component within the incoming halo determines its tidal stripping position in the big halo and thus its final remaining baryonic spin after the merger. The finding that the low-$j$ material originates in many minor mergers, that tend to cancel each other’s $J$, provides the clue for a possible solution to the $j$-profile mismatch problem. The blowout of gas from small incoming halos, which is more pronounced in satellites of dwarfs, would eliminate the low-$j$ baryons in the merger product and increase the spin parameter, as observed.

The feedback effects, including heating and blowout, are modeled as a function of halo virial velocity, with one free parameter — the characteristic velocity $V_{\text{fb}}$ corresponding to the feedback energy from supernovae. To match the low baryonic fraction observed in dwarfs it has to be $V_{\text{fb}} \sim 100 \, \text{km} \, \text{s}^{-1}$, consistent with the theoretical predictions [8]. This leads to an agreement between the model predictions and the observed disks, for the distribution of baryonic spin among galaxies and the baryonic $j$ distribution within galaxies, both dwarfs and bright galaxies.

We attempt to resolve the problems within the successful cosmological framework of CDM, by appealing to inevitable feedback effects. Another approach is to appeal to the Warm Dark Matter (WDM) scenario, despite the fact that it requires fine-tuning of the particle mass to $\sim 1 \, \text{keV}$. The main feature of WDM is the suppression of small halos and the corresponding mergers. While an N-body simulation of WDM [2] indicates the same $j$ properties of halos (the same properties can also be obtained as a general result of tidal-torque theory, see MDS), one expects the cooling to be less efficient in the absence of small halos, and thus the baryonic spin to be higher. However, the $j$ profile is still expected to be a problem, and the weaker feedback effects in the absence of small halos may not be enough for resolving it. These issues are yet to be studied in hydro simulations of WDM.

Feedback effects may also provide the cure to the missing dwarf problem in CDM, where the predicted number of dwarf halos is much larger than the ob-
served number of dwarf galaxies [3]. While the number of dwarfs is automatically suppressed in WDM, it seems that the inclusion of the minimum inevitable feedback effects would reduce the predicted number of dwarfs to significantly below the observed number and thus be an overkill (J. Bullock, private comm.). Finally, we find [7] that the key elements of our toy model — the tidal effects in mergers and the feedback in small halos — are also very relevant in understanding and resolving the third problem of CDM, where the halos in simulations typically show steep cusps in their inner profiles [14], while observations indicate flat cores at least in some galaxies [4]. An analysis of tidal effects explains the inevitable formation of an asymptotic cusp as long as satellites continue penetrating into the halo center. Feedback effects may puff up small satellites, make them disrupt in the outer halo and thus allow a stable core.

The success of our toy model in matching several independent observations indicates that it indeed captures the relevant elements of the complex processes involved, and in particular that feedback effects may indeed provide the cure to all three problems of galaxy formation in CDM. The next natural step should be to incorporate a more sophisticated feedback recipe into the model using semi-analytic models and then full-scale cosmological simulations.

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