Part 14
Angular Momentum

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The Origin and Distribution of Angular Momentum in Galaxies

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Abstract. Cold Dark Matter with a large cosmological constant (ΛCDM) appears to fit large scale structure observations well. Of the possible small scale problems, the *Central Cusps* and *Too Many Satellites* problems now appear to be at least partly solved, so *Angular Momentum* has become the most serious remaining CDM problem. There are actually at least two different angular momentum problems: A. Too much transfer of angular momentum to the dark halo to make big disks, and B. Wrong distribution of specific angular momentum to make spiral galaxies, if the baryonic material has the same angular momentum distribution as the dark matter. The angular momentum of dark matter halos, and presumably that of the galaxies they host, appears to arise largely from the orbital angular momentum of the satellites that they accrete. Since the dark and baryonic matter behave very differently in such accretion events, it is possible that the resulting angular momentum distribution of the baryons is different from that of the dark matter, as required to make the sort of galactic disks that are observed. The latest hydrodynamical simulations give some grounds for hope on this score, but much higher resolution simulations are needed.

1. Too Much Transfer of Angular Momentum to the Dark Matter to Make Big Disks

1.1. History

This phenomenon was described by Navarro & Benz (1991) and Navarro & Steinmetz 1997. It appears to be due at least in part to the unphysically rapid cooling of gas when feedback from star formation is neglected. When gas is prevented from cooling before $z = 1$, more realistic disks form (Weil, Eke, & Efstathiou 1998; Eke, Efstathiou, & Wright 2000), as also can happen with cooling when feedback is treated in simple ways (Thacker & Couchman 2001; Maller & Dekel 2002). More realistic disks may form even without feedback in higher resolution simulations (Governato et al. 2002), although even with feedback many of the baryons still formed a big bulge in one simulation (Abadi et al. 2003a, b). The merging history and the nature of the assumed feedback evidently matter!

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1.2. Origin of the Angular Momentum Problem Transfer Problem: Overcooling?

Overcooling in merging satellites can explain why the baryons in simulations lose much of their angular momentum to the dark matter. If the baryons are more concentrated than the DM in the satellites, the DM will be tidally stripped and the baryons will lose energy and angular momentum by dynamical friction. This is illustrated in Figure 1. But if stellar feedback prevents the gas from cooling in small accreted satellites, then the gas rather than the DM will be preferentially stripped at large radius, and the gas may retain its angular momentum.

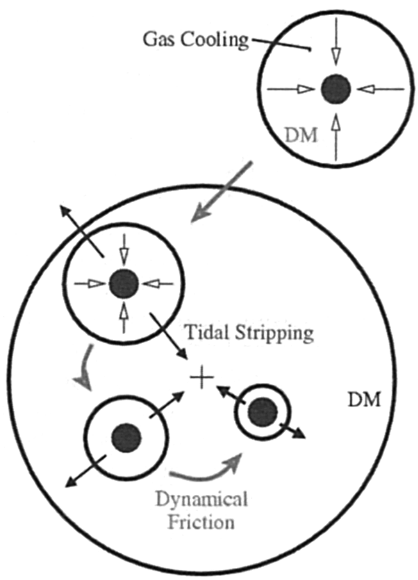

Figure 1. Overcooling model (Maller & Dekel 2002).

2. Wrong Distribution of Specific Angular Momentum to Make Spiral Galaxies

As part of James Bullock's dissertation research, we found that the distribution of specific angular momentum j in dark matter halos has a universal profile, described by the equation below and illustrated in Fig. 2(a), in which much of the DM has low j but there is also a high j tail (Bullock et al. 2001):

$$M(<j) = M_v \frac{\mu j}{j_0 + j} , \qquad \mu > 1 . \tag{1}$$

This profile has $j_{\max} = j_0/(\mu - 1)$. It is roughly power-law for $j < j_0$ and flattens out for $j > j_0$. The quantity μ (> 1) is a shape parameter: for $\mu \gg 1$, $M(<j)$ is a pure power law, while for $\mu \longrightarrow 1$ only half the mass falls in the power-law

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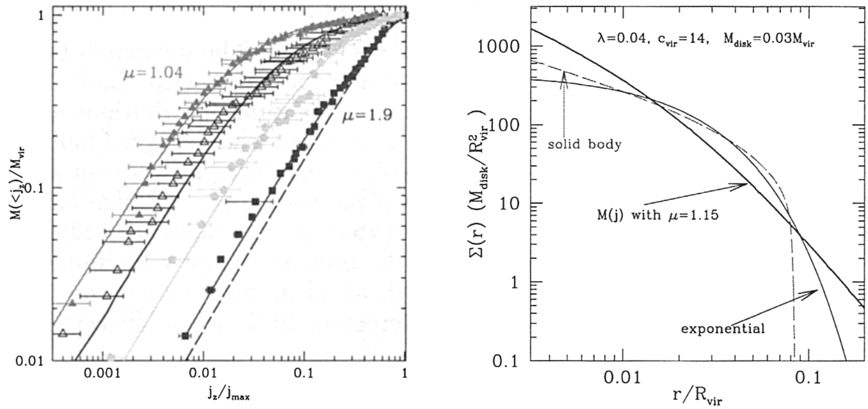

Figure 2. (a) Mass distribution of angular momentum in four halos spanning a range of μ values from 1.04 to 1.9. The curves are the functional fits, eq. (1). Profiles are normalized to coincide at M_v, where $j = j_{\max}$. The distribution for a uniform sphere in solid body rotation is shown for comparison (dashed line). (b) Typical disk surface-density profile implied by our universal $M(< j)$ distribution for typical $\mu = 1.25$, assuming that j is conserved during baryonic infall (Mestel). There is much more material at small r than in an exponential disk, and also a tail to large r. (Bullock et al. 2001.)

regime and there is a pronounced bend. We find that $\log(\mu - 1)$ has a Gaussian distribution with mean 0.6 ($\langle\mu\rangle = 1.25$) and $\sigma = 0.4$.[1]

2.1. Implications for Galactic Disks

If the baryons that become the visible parts of galaxies have the same angular momentum distribution as the DM, they could not form the observed rotationally-supported disks. This is illustrated in Figure 2(b).

It has long been assumed that baryons and DM in a halo start with a similar angular momentum distribution, based on the idea that the angular momentum arising from large scale tidal torques will be similar across the entire halo. But this may not be true if the angular momentum of halos grows mainly from the orbital angular momentum of accreted satellite halos, as we recently proposed (Vitvitska et al. 2002). We discuss this further below.

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[1] Other groups (Chen & Jing 2002; Chen, Jing, & Yoshikawa 2003) have confirmed our universal profile $M(< j)$, although they find that some halos have a significant amount of negative j material (rotating in the opposite sense), which could exacerbate the angular momentum profile problem. This is probably partly a resolution issue, and partly an issue of methodology. The fraction of mass with j negative is much larger using the Particle method (as in van den Bosch et al. 2003a,b) than using the Cell method (as in Bullock et al. 2001). But I do not understand the logic of the Particle method applied to gas particles; if gas particles had the large random momenta assigned in this approach, they would constantly collide and shock.

2.2. Does Taking Bulges Into Account Help?

Of course, some of the low j baryons will form bulges. The mismatch between the surface density profiles $\Sigma(r)$ is most severe for halos with small $\mu \approx 1$, which also tend to have mis-aligned angular momentum distributions and are therefore less likely hosts of spiral galaxies. But even for well-aligned halos with $\mu > 1.1$, the implied central densities are still higher than in exponential disks (Fig. 2b). And assuming that all the low-j material forms a bulge (van den Bosch et al. 2003a,b) results in B/D ratios that are too high, with almost no pure disk galaxies like M33. Moreover, in the previous figure we assumed that angular momentum is conserved. Any transfer of angular momentum to the dark matter (as seen e.g., by Navarro & Steinmetz 1997) would exacerbate the problem.

3. Solutions?

Only for shape parameter $\mu \gtrsim 2$, which occurs for fewer than 10% of halos, does the surface density $\Sigma(r)$ look like the exponential of observed disk galaxies. If CDM is right, then either the baryons have a j distribution rather different from that of the dark matter, or only a special subset of the baryons in the halo forms the disk, or both.

How do forming halos actually acquire their angular momenta? Vitvitska et al. (2002) proposed and investigated the hypothesis that it mostly comes from the orbital angular momentum of accreted satellite halos. If so, since the dark matter particles pass through each other while the baryons shock during the hierarchical merging process through which structure forms in CDM, then it would actually be rather plausible that these two components will have a different distribution of specific angular momentum j. Such different distributions could start to arise at high redshift (van den Bosch et al. 2003a,b).

3.1. Origin of Angular Momentum J in Dark Matter Halos

The standard picture is that J arises from tidal torques (Peebles 1969; Doroshkevish 1970; White 1984). This is no doubt true at some level, but this model incorrectly predicts both the amplitude (Barnes & Efstathiou 1987; Sugarman et al. 2000) and the direction (Lee & Pen 2000; Porciani et al. 2002). An improved version of the tidal torque model still predicts dependence of λ on mass, redshift, and cosmology, in disagreement with simulations (Maller, Dekel, & Somerville 2002).

3.2. Halo Mass Accretion Histories

In her dissertation research with me, Risa Wechsler (Wechsler et al. 2002) investigated the formation history of every large dark matter halo in the same high-resolution cosmological simulation that James Bullock had earlier analyzed. The result was several thousand structural merger trees, including the merging halos structural properties such as the radial distribution of the dark matter (NFW concentration parameter) and the angular momentum (spin parameter). This allowed us to explain how the concentration of a halo is related to its mass

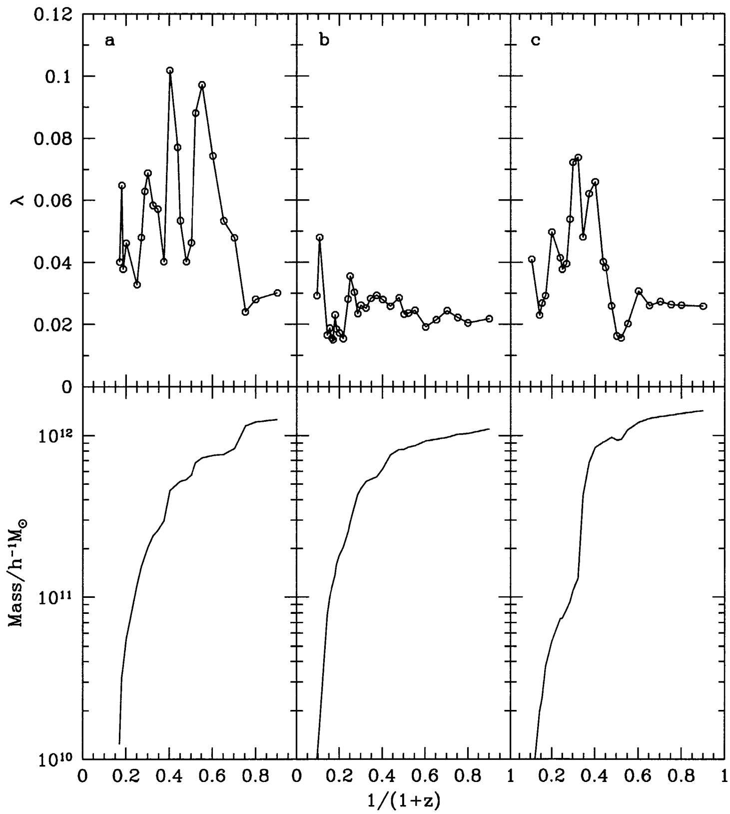

Figure 3. Mass accretion (lower panels) and spin parameter evolution (upper panels) of three galaxy-mass halos. Halos typically show fast mass growth at high redshift with rapid changes of spin parameter, followed by slower mass accretion with spin parameter usually declining. (From Vitvitska et al. 2002.)

accretion history (also subsequently studied by van den Bosch 2002 and Zhao et al. 2003).

Briefly, we found that

- There is an early epoch of rapid mass accretion often involving major mergers: the central region acquires a density similar to the background density at that epoch.

- A subsequent epoch of slow mass accretion by minor mergers mainly builds the outer part of the dark matter halo with $r > r_s$, increasing the concentration of the halo: $C_v = R_v/r_s$.

We are incorporating this information into semi-analytic modeling of galaxy formation, where it has significant effects.

We also investigated how the angular momentum of halos is related to their mass accretion histories; the results were reported in Vitvitska et al. (2002). We studied the evolution of three 10^6 particle halos of mass $\sim 10^{12} M_\odot$, shown in Fig. 3 here, and also hundreds of halos in a large simulation. The spin parameters

$$\lambda \equiv \frac{J|E|^{1/2}}{GM^{5/2}}, \quad \lambda' \equiv \frac{j}{\sqrt{2} M_{\rm vir} V_c R_{\rm vir}} \tag{2}$$

typically have sharp increases (or sometimes decreases) due to major mergers during the early rapid accretion phase of halo growth, and a steady decline during the subsequent slower accretion. Halos typically have rapid increases of λ in major mergers if λ is small, but λ decreases if λ is large. The spin parameter λ typically shows big jumps due to major mergers, and slow decline during the slow mass accretion epoch due to random orientations of orbital angular momenta of accreted satellites.

4. Random Walk Model of Angular Momentum Growth

In order to model the angular momentum history of halos as due to accretion in Vitvitska et al. (2002), we measured the velocity anisotropy parameter of the incoming satellites, finding $\beta \approx 0.6$, and also the dependence of of the satellite orbital angular momenta on the satellite internal velocity. We checked that the incoming directions of satellites are essentially random, and used the Extended Press-Schechter approximation to model halo mass accretion histories. We found that the resulting pattern of spin parameter evolution is similar to that in high-resolution N-body simulations. We then calculated the λ distribution in this *random walk* model of halo angular momentum growth, and found it to agree very well with N-body simulations.

Our random walk angular momentum accretion model agrees with N-body simulations in the resulting spin parameter distribution (Vitvitska et al. 2002; Maller, Dekel, & Somerville 2002). Maller & Dekel (2002) showed that a simplified version also leads to halos having the j distribution seen in simulations. It is interesting that the random walk model predicts that halos that had a major merger have higher λ. This may lead to an elliptical galaxy paradox, and it makes interesting predictions that can be compared to new data on the rotation of halos hosting elliptical galaxies (see Vitvitska et al. 2002).

5. Possible Solutions to the Angular Momentum Distribution Problem

5.1. Solving Angular Momentum Problems Via Feedback

It is the late mass accretion of small halos that generates much of the low angular momentum material in big halos. Maller & Dekel (2002) point out that in small halos supernova feedback is especially effective in preventing gas from cooling, unlike in the Fig. 1 cartoon. Consequently, the gas in small halos will be less concentrated than the DM, so the gas is stripped before it reaches the center of the halo. They found that feedback characterized by a parameter $V_{fb} = 95\ \mathrm{km\,s^{-1}}$ reduces the gas content of dwarf galaxies to observed levels, and also results in a higher spin for dwarf galaxies than giants, as observed (van den Bosch, Burkert, & Swaters 2001). Massive galaxies are able to retain a much higher baryonic fraction in this model, again in agreement with observations. The Maller & Dekel (2002) feedback model with $V_{fb} = 95$ km s^{-1} predicts disk mass fractions for dwarf galaxies in good agreement with observations, and well below the typical DM j distribution at both low and high j.

5.2. Some Alternative Solutions to the j Distribution Problem

Note that most of the visible baryonic mass is in spheroids with low angular momentum, and that most of the baryonic mass does not end up in the visible parts of galaxies. What is needed to make observed disks is for them to form from the baryons with the *right* angular momenta.

This could happen if the low angular momentum material forms a central concentration which is then blown out because of a starburst. But is this likely in dwarfs, for which the angular momentum distribution problem is most severe?

An alternative suggested by Katz et al. (2003) and by Birnboim & Dekel (2003) is that the baryonic material in most disk galaxies is fed in rather cold (without virial shocks) from filaments, as mentioned by Franoise Combes in her talk at this meeting. But it is unclear why the angular momenta of the accreted gas should be coherent enough to solve the angular momentum distribution problem.

The most optimistic alternative is perhaps that discussed by Barnes (2002), which suggests that in hydrodynamic simulations of major mergers of disk galaxies, the tidal tails have enough baryonic material with large enough angular momentum to build realistic disks. However, this was based on simulations in which the gas was assumed to be isothermal; my group is finding that it may not be typically true in more realistic simulations including shock-heating of the gas (Cox et al. 2003).

6. Hydro Simulations: Do Baryons Have a Different j Distribution?

The first hydrodynamic simulations including cooling to address the angular momentum distribution problem have just been reported by Chen, Jing, & Yoshikawa (2003). They find that the hot gas has less negative j, and a distribution of angular momentum that is much more favourable for disk formation than that of the dark matter or the cold gas. Some examples are shown in Fig. 3. However, the halos in their simulation with adequate resolution are group-mass systems. This would be good news for disk galaxy formation if, in galaxy-mass halos, much of this hot gas has enough time to cool so that it can make galactic disks that are as old as they are typically observed to be – which remains to be seen.

The shape parameter μ is much higher for hot gas than dark matter in these hydro simulations (recall that $\mu \gtrsim 2$ is needed to get an approximately exponential disk). *If* the hot gas in these group-size halos corresponds to the gas that forms disks in typical galaxies, this suggests that the gas will be able to form realistic disks, even if it loses some of its angular momentum.

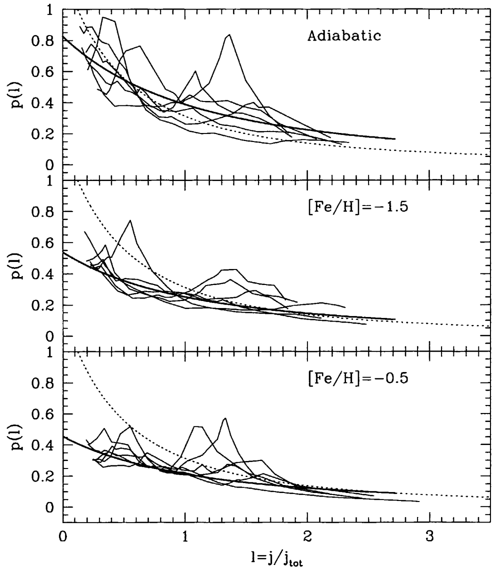

Figure 4. Angular momentum distribution of gas in nonradiative cases (upper panel) and the hot gas fraction of all gas in cooling simulations (lower two panels; the lower, higher metallicity case cools faster). Here $l = j/j_{\rm tot}$, where $j_{\rm tot} \equiv \langle j \rangle$ of hot gas. The dotted and solid lines represent $\mu = 1.25$ (typical dark matter value) and $\mu = 1.8$ (needed to form a roughly exponential disk). (From Chen, Jing, & Yoshikawa 2003.)

7. Conclusions, Caveats, and Outlook

- The Maller & Dekel (2002) model may capture the main cause of the angular momentum transfer problem, and it suggests that inclusion of feedback may solve it.

But this model is oversimplified and thus far only beginning to be tested by hydro simulations (van den Bosch et al. 2003a,b).

- The random walk model of the origin of halo angular momentum from the orbital angular momentum of accreted satellites (Vitvitska et al. 2002) fits N-body simulation results. It offers hope that gas shocking may lead to the baryons having a different specific angular momentum j distribution from the dark matter, as required to form galactic disks like those observed.

But thus far hydro simulations have not found this for all the gas, and *most importantly* for the gas that actually forms galactic disks.

- Chen, Jing, & Yoshikawa (2003) find that the hot gas in group-size halos does have the sort of j distribution that is needed to form exponential disks.

But it is not clear that this hot gas has anything to do with galactic disks. Higher resolution hydrodynamic simulations are clearly needed.

- Since only part of the gas in halos forms the visible material in galaxies, we can solve the j distribution problem by choosing the *right* gas.

But so far we have little understanding of whether and why nature may do so. This is perhaps the biggest challenge for CDM!

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