The Cosmological Angular Momentum Problem of Low-Mass Disk Galaxies

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The rotational properties of the visible and dark components of low-mass disk galaxies \((v_{\text{rot}} \leq 100 \text{ km/s})\) are investigated using the Swaters sample. The rotational parameter \(\lambda' = \lambda_j / m_d\) is determined, where \(\lambda\) is the dark halo spin parameter and \(j_d / m_d\) is the ratio between the specific angular momentum of the disk and that of the dark halo. The distribution of \(\lambda'\) is in excellent agreement with cosmological predictions of hierarchical clustering if \(j_d / m_d \approx 1\), that is, if the protogalactic gas did not lose a significant amount of specific angular momentum due to dynamical friction. This result is in disagreement with current cosmological Nbody/SPH simulations where the baryonic component loses 90\% of its specific angular momentum while settling into the equatorial plane. The Swaters sample also shows a surprisingly strong correlation between \(\lambda'\) and the baryonic mass fraction \(m_d\): \(\lambda' = 0.4m_d^{0.6}\). This correlation can be explained if the total amount of gas in protogalaxies is a universal fraction of their dark matter mass, of order 10\%, and if the variation in \(m_d\) is a result of the fact that only the inner parts of the primordial gas distribution managed to form a visible disk component. In this case the specific angular momentum of the gas out of which the disk formed is a factor of 2.75 larger than that of the dark halo, which would require a yet unknown spin-up process for the visible baryonic component.

Subject headings: cosmology: theory – dark matter – galaxies: evolution – galaxies: formation – galaxies: structure
1. Introduction

Cosmological models of hierarchical clustering predict that galactic disks form as a result of gas infall into cold dark matter (CDM) halos. The disk scale lengths and rotation curves are determined by the gravitational potential and by the specific angular momentum distribution which the gas acquired from tidal interaction with the cosmological density field (Peebles 1969) and which was modified during the protogalactic collapse phase. As gas and dark matter were equally distributed initially, it is generally assumed that both components obtained similar amounts of specific angular momentum. Indeed, analytical calculations (e.g. Fall & Efstathiou 1980, Mo, Mao & White 1998, Mo & Mao 2000, Buchalter et al. 2000) have shown that this condition can explain the observed scale lengths and various other properties of galactic disks, provided that the disk material retained its initial specific angular momentum when settling into the galactic plane and that the dark matter halos are not too centrally condensed.

In the past couple of years detailed numerical calculations have however uncovered serious problems with the CDM scenario. In a seminal paper, Navarro, Frenk & White (1997) found that dark matter halos have universal density profiles that can be approximated by the empirical formula \( \rho(r) = \rho_0 r_s^2 / (r(r + r_s)^2) \) (hereafter the NFW profile), where \( r_s = R_{200}/c \) is the scale radius, \( c \) is the concentration and \( R_{200} \) is the virial radius of the dark matter halo, defined as the radius inside which the average dark matter density is 200 times the mean density of the universe. NFW found high concentrations of \( c \approx 10 - 15 \). Recent higher resolved simulations give even larger values of \( c \approx 15 - 20 \) (Moore et al. 1999, Navarro & Steinmetz 2000). Other simulations (e.g. by Fukushige & Makino (1997), Moore et al. 1998, Ghigna et al. 1999, Klypin et al. 2000) confirmed that DM halos are very centrally concentrated and found even steeper inner slopes of \( \rho \sim r^{-1.5} \). These predictions provide strong constraints for the slopes of galactic rotation curves and it was noted by
Flores & Primack (1994) and Moore (1994, see also Burkert 1995; McGaugh & de Block 1998) that NFW halos with high concentrations disagree with the rotation curves of dark matter dominated dwarf galaxies which rise more slowly than theoretically expected.

High-resolution cosmological N-body/SPH simulations have also exposed the formation of galactic disks to another problem: the scale lengths and specific angular momenta of simulated disks are a factor of 10 smaller than observed (Weil, Eke & Efstathiou 1998, Navarro & Steinmetz 1997, Sommer-Larsen, Gelato & Vedel 1999). This so called angular momentum problem of galaxy formation arises from the fact that the gas cools efficiently during the protogalactic collapse phase, leading to dense clumps that lose a large fraction of their angular momentum to the dark halo by dynamical friction while sinking towards the center.

Both, the halo concentration and disk angular momentum problem seem to provide serious challenges for CDM and have encouraged the investigation of numerous alternative models, including exotic dark matter properties (e.g. Spergel & Steinhardt 2000, Goodman 2000, Cen 2000, Peebles 2000, see however Dalcanton & Hogan 2000) or the presence of a second dark baryonic spheroid (Burkert & Silk 1997). The situation has recently changed again due to new, high-resolution observations of rotation curves. Van den Bosch et al. (2000) and van den Bosch & Swaters (2000) showed that the inner HI rotation curves of low-surface brightness (LSB) galaxies become significantly steeper when observed with higher resolution and when the effects of beam smearing are properly taken into account. In contrast to previous claims, the LSB rotation curves seem to be consistent with NFW profiles, although \( r^{-1.5} \)-cusps might still provide a problem. Swaters, Madore & Trehella (2000) presented H\( \alpha \) rotation curves of LSB galaxies which also rise more steeply than the previously derived HI profiles and which are consistent with the concept of a universal rotation curve (Persic, Salucci & Stel 1996). In summary, at least for lower-mass galaxies
the cosmologically predicted halo profiles are not in serious conflict with the observations anymore and the angular momentum problem has become the main challenge for the CDM scenario.

One possibility to solve this problem is to assume energetic feedback processes which keep the gas in a diffuse state, preventing angular momentum loss by dynamical friction. These processes have however not proven to be very efficient. Sommer-Larsen, Gelato & Vedel (1999) demonstrated that the disks are still too small in simulations where 80% or more of the final disk mass is accreted from hot, dilute gas. The situation does only improve if the gas would be completely blown out of the galactic halos at high redshifts. Navarro & Steinmetz (2000) took into account realistic feedback processes and found a minor impact on the angular momentum problem.

The angular momentum problem has been investigated in the past preferentially for higher mass galaxies with rotational velocities $v_{rot} > 100$ km/s which suffer from large uncertainties in the disk-halo decomposition (Syer, Mao & Mo 1999). Recently, van den Bosch & Swaters (2000) published accurate disk and halo parameters for a sample of late-type dwarf galaxies with $v_{rot} \leq 100$ km/s. Using their results, the rotational properties of the dark halo and the disk in dwarf spirals are investigated and compared with theoretical predictions in Section 2. Section 3 shows that there exists a strong correlation between the rotational parameter $\lambda'$ and the disk mass fraction $m_d$. A simple model of gas infall and disk formation is presented which can explain this correlation. A discussion of the results and conclusions follow in Section 4.
2. The Rotational Properties of the Dark and Luminous Components in Dwarf Spiral Galaxies

Van den Bosch & Swaters (2000) presented a careful analysis of the rotation curves of 20 late-type dwarf galaxies studied by Swaters (1999). Taking into account the effects of beam smearing and adiabatic contraction they determined the concentration $c$ and the virial velocities $v_{200}$ of the dark matter halos which they found to be consistent with the predictions of $\Lambda$CDM models. In addition, the disk scale lengths $R_d$ and the disk halo mass fractions $m_d$ were determined. In the following we will analyse those galaxies for which a meaningful fit could be achieved (marked by "+" in the paper by van den Bosch & Swaters 2000), adopting a stellar R-band mass-to-light ratio of $\Upsilon_R = 1$.

If one assumes that the surface density distribution of the disks is exponential and that the dark matter halos initially followed an NFW profile and responded to the growth of the disk adiabatically, one can derive an expression for the product of the dimensionless dark matter spin parameter $\lambda$ and the specific disk angular momentum $j_d/m_d$ (Mo, Mao & White 1998)

$$\lambda' = \lambda \left( \frac{j_d}{m_d} \right) \approx \frac{\sqrt{2} R_d h}{f_R v_{200}} \left( \frac{2}{3} + \frac{c}{21.5} \right)^{0.7} \lambda^{0.5}$$  (1)

where $h = 0.75$ is the Hubble constant normalized to 100 km/s/Mpc, $j_d$ is the ratio of the total angular momentum of the disk with respect to that of the dark halo and

$$f_R \approx (10\lambda')^{-0.06+2.71m_d+0.0047/\lambda'}$$  (2)

The crosses in Figure 1a show the distribution of $\lambda'$. Unfortunately only the product of $\lambda$ and $j_d/m_d$ can be determined directly. It is however generally assumed that the gas initially obtained the same specific angular momentum as the dark halo and that it conserved its
angular momentum when settling into the equatorial plane. In this case, \( j_d/m_d = 1 \) and Figure 1a shows directly the dark halo \( \lambda \) distribution. The solid line in this figure indicates the theoretically predicted \( \lambda \)-distribution using the approximation (Mo, Mao & White 1998)

\[
N(\ln(\lambda)) \sim \exp\left(-\frac{\ln^2(\lambda/\bar{\lambda})}{2\sigma^2_{\lambda}}\right)
\]  

with \( \bar{\lambda} = 0.04 \) and \( \sigma_{\lambda} = 0.5 \). The observations are in excellent agreement with the predictions of cosmological models. This result indicates clearly that dwarf spiral galaxies have an angular momentum problem and that the gas could not lose a significant amount of its angular momentum during the protogalactic collapse phase, in contradiction to current cosmological N-body/SPH calculations (Navarro & Steinmetz 1997, Sommer-Larsen, Gelato & Vedel 1999).

3. The Correlation between \( \lambda' \) and the Disk Mass Fraction \( m_d \)

The data contains even more information. Figure 1b plots \( \lambda' \) versus \( m_d \) which reveals a surprisingly strong correlation. A least squares fit leads to

\[
\lambda' = \lambda \left( \frac{j_d}{m_d} \right) = 0.4 m_d^{0.6}
\]

which is shown by the dashed line in Figure 1b.

One can think of several possibilities to explain this relationship. The sample of dwarf galaxies studied by van den Bosch & Swaters (2000) could be subject to selection effects. Figure 1a demonstrates however that the data is not biased with respect to the dark halo spin parameter \( \lambda \). If \( j_d/m_d \approx 1 \) selection effects cannot affect \( \lambda' \) and it is not clear how they could provide an explanation for equation 4.
For \((j_d/m_d) \approx 1\), equation 4 would indicate a correlation between the halo spin parameter \(\lambda\) and the disk mass fraction \(m_d\). Such a relationship is not predicted by cosmological models.

Another, maybe more promising solution is the assumption that equation 4 results from a strong correlation between the specific disk angular momentum \((j_d/m_d)\) and \(m_d\), with the halo spin parameter \(\lambda\) being independent of \(m_d\). Then, the scatter around the dashed curve in Figure 1b reflects the cosmological scatter in \(\lambda\) and the dashed curve represents its mean value of \(\lambda \approx 0.04\). With \(\lambda = 0.04\), equation 4 leads to

\[
\frac{j_d}{m_d} = 2.5 \left(\frac{m_d}{0.1}\right)^{0.6} .
\] (5)

There exists a simple explanation for this relationship. Let us assume that the total gas-to-dark matter mass ratio \(f_g\) in protogalaxies was universal \(f_g = M_g/M_{DM} \approx 0.1\), that however only some fraction \(m_d/f_g\) of the total gas mass, located initially inside some radius \(r_d\) of the protogalaxy formed a visible disk component. If one adopts a standard top-hat model where the distribution of gas and dark matter at the onset of the protogalactic collapse phase can be approximated by a homogeneous, rigidly rotating sphere with total radius \(R\), the specific angular momentum of the gas inside \(r_d \leq R\) is \((J/M)_g = 0.4\omega_g r_d^2\) where \(\omega_g\) is the angular velocity of the gas sphere. The specific angular momentum of the dark component is given by \((J/M)_{DM} = 0.4\omega_{DM} R^2\) with \(\omega_{DM}\) the specific angular velocity of the dark matter. As the mass fraction of gas inside \(r_d\) is \(m_d/f_g = (r_d/R)^3\) we find

\[
\left(\frac{j_d}{m_d}\right) = \frac{(J/M)_g}{(J/M)_{DM}} = \frac{\omega_g}{\omega_{DM}} \left(\frac{m_d}{f_g}\right)^{2/3}
\] (6)

which has the same power-law dependence as equation 5.
4. Discussion of the Results and Conclusions

The previous analysis leads to some interesting conclusions which might be useful for further studies of the cosmological angular momentum problem.

The observed disk mass ratios are $m_d \leq 0.1$ which implies that this value is a lower limit for the universal primordial gas fraction in protogalaxies, i.e. $f_g \geq 0.1$. In many dwarf spiral galaxies $m_d$ is much smaller than 0.1. Most of their primordial gas might therefore not have contributed to the visible disk component. This gas could still be around in a diffuse state or it could have been blown out by galactic winds.

Adopting $\lambda = 0.04$, a good fit to the observed correlation (Figure 1b) can be achieved if

$$\frac{\lambda}{0.04} = \frac{j_d}{m_d} = 2.75\left(\frac{m_d}{0.1}\right)^{2/3}. \tag{7}$$

This relationship is shown by the dotted line in Fig. 1b. Comparing equation 7 with equation 6 leads to

$$\frac{\omega_g}{\omega_{DM}} \approx 2.75\left(\frac{f_g}{0.1}\right)^{2/3}. \tag{8}$$

As $f_g \geq 0.1$ the gas out of which the galactic disks formed either was rotating faster than the dark halos ($\omega_g \geq 2.75\omega_{DM}$) initially or it gained angular momentum later on. Note that all galaxies in the present sample must have experienced the same spin-up event in order to explain the strong correlation observed.

Up to now, it is not clear which processes could have increased the specific angular momentum of the gaseous components beyond that of the dark halos. One possibility might be selective mass loss in galactic winds which might have ejected preferentially the low angular momentum gas, leaving behind disks with high specific angular momentum (van
den Bosch, private communication). Although this scenario is interesting it is not clear how the angular momentum - mass relationship (equation 4) could be explained within the framework of this model. In addition, galaxies with large values of $m_d = 0.1 \approx f_g$ probably did not lose a significant amount of gas. Yet they have the highest values of $\lambda' = 0.1$ and therefore the highest specific angular momenta of all dwarf spirals.

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Fig. 1.— Figure 1a compares the distribution of $\lambda' = \lambda(j_d/m_d)$ of the Swaters sample (crosses) with the predictions of cosmological models adopting $(j_d/m_d) = 1$ (solid line). Figure 1b shows as open starred symbols the correlation between $\lambda'$ and the disk mass fraction $m_d$ for the Swaters sample. The dashed curve represents a linear least squares fit through the data. The dotted line shows the predicted relationship for the model discussed in the text.