FORMATION OF DISK GALAXIES: ON THE ANGULAR MOMENTUM PROBLEM, THE TULLY-FISHER RELATION AND MAGNETOHYDRODYNAMICS

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Abstract. Two ways of possibly solving the angular momentum problem plaguing cold dark matter (CDM) ab initio simulations of disk galaxy formation are discussed: 1) Stellar feedback processes and 2) Warm dark matter (WDM) rather than CDM.

In relation to the chemical evolution of disk galaxies our simulations indicate that in case 1) the first generation of disk stars formed in disk galaxies like the Milky Way should have an abundance about two dex below solar, in fairly good agreement with the lowest observed abundance of the metal-weak tail of the Galactic thick disk. For the second case no such statements can be made without further assumptions about the star-formation history of the galaxies.

We find that the $I$-band Tully-Fisher relation can be matched by WDM disk galaxy formation simulations provided $(M/L)_I \sim 0.8$ for disk galaxies, which Sommer-Larsen & Dolgov (1999) argue is a reasonable value.

Finally it is discussed how the magnetic field strengths observed in galactic disks can be obtained through disk galaxy formation, as an alternative to the conventional dynamo hypothesis.

1. Introduction

The formation of galactic disks is one of the most important unsolved problems in astrophysics today. In the currently favored hierarchical clustering framework, disks form in the potential wells of dark matter halos as the baryonic material cools and collapses dissipatively. Fall & Efstathiou (1980) have shown that disks formed in this way can be expected to possess the
observed amount of angular momentum (and therefore the observed spatial extent for a given mass and profile shape), but only under the condition that the infalling gas retain most of its original angular momentum.

However, numerical simulations of this collapse scenario in the cold dark matter (CDM) cosmological context (e.g., Navarro & Benz 1991, Navarro & White 1994, Navarro, Frenk, & White 1995) have so far consistently indicated that when only cooling processes are included the infalling gas loses too much angular momentum (by over an order of magnitude) and the resulting disks are accordingly much smaller than required by the observations. This discrepancy is known as the angular momentum problem of disk galaxy formation. It arises from the combination of the following two facts: a) In the CDM scenario the magnitude of linear density fluctuations $\sigma(M) = \langle(\delta M/M)^2\rangle^{1/2}$ increases steadily with decreasing mass scale $M$ leading to the formation of non-linear, virialized structures at increasingly early epochs with decreasing mass i.e. the hierarchical “bottom-up” scenario. b) Gas cooling is very efficient at early times due to gas densities being generally higher at high redshift as well as the rate of inverse Compton cooling also increasing very rapidly with redshift. a) and b) together lead to rapid condensation of small, dense gas clouds, which subsequently lose energy and (orbital) angular momentum by dynamical friction against the surrounding dark matter halo before they eventually merge to form the central disk. A mechanism is therefore needed that prevents, or at least delays, the collapse of protogalactic gas clouds and allows the gas to preserve a larger fraction of its angular momentum as it settles into the disk. Two such possible solutions are discussed in section 2.

In section 3 we present some new results from our WDM disk galaxy formation simulations on the Tully-Fisher relation and in section 4 we discuss how the magnetic field strengths of a few $\mu$G observed in galactic disks can be obtained via disk galaxy formation, as an alternative to disk dynamo amplification.

2. Towards solving the angular momentum problem

Two ways of possibly solving the angular momentum problem have recently been discussed in the literature: a) by invoking the effects of stellar feedback processes from either single, more or less uniformly distributed stars or starbursts and b) by assuming that the dark matter is “warm” rather than cold. Both options lead to the suppression of the formation of early, small and dense gas clouds, for a) because the small gas clouds may be disrupted due to the energetic feedback of primarily type II super-nova explosions and for b) simply because fewer of the small and dense gas clouds form in the first place for WDM free-streaming masses $M_{f,WDM} \sim 10^{10} - 10^{11} M_\odot$. 
Figure 1. The initial disk oxygen abundance resulting from infall of a mixture of enriched and unenriched gas onto the disk of a forming, Milky Way sized model galaxy. This abundance should be representative of the oxygen abundance of the first generation of disk stars formed and is fairly consistent with the lowest found observationally for the metal-weak tail of the Galactic thick disk.

2.1. STELLAR FEEDBACK PROCESSES

Sommer-Larsen et al. (1999) showed that the feedback caused by a putative, early epoch of more or less uniformly distributed population III star formation was not sufficient to solve the angular momentum problem. Based on test simulations they showed, however, that effects of feedback from starbursts in small and dense protogalactic clouds might do that. Preliminary results of more sophisticated simulations incorporating stellar feedback processes in detail indicate that this is at least partly the case. Considerable fine-tuning seems to be required, however: About 2-3% of the gas in the
proto-galactic region of a forming disk galaxy should be turned into stars. If less stars are formed the feedback is not strong enough to cure the angular momentum problem and, vice versa, if more stars are formed during this fairly early phase of star-formation, the energetic feedback causes the formation of the main disks and thereby the bulk of the stars to be delayed too much compared to the observed star-formation history of the Universe.

This requirement of fine-tuning is advantageous, however, in relation to the early chemical evolution of disk galaxies, since the early star-formation histories of the galaxies are then well constrained. Furthermore, as it is possible to track the elements produced and ejected by (primarily) type II supernovae in the star-bursts one can determine the fraction of these elements, which ultimately settle on the forming disk and hence determine the rate and metallicity of the gas falling onto the disk. In Figure 1 we show the time evolution of the oxygen abundance in a forming disk as a result of infall of a mixture of enriched and unenriched gas (neglecting the contribution of ejecta from stars formed subsequently in the disk). We have assumed a Salpeter IMF with \( M_{\text{low}} = 0.1 M_\odot \) and \( M_{\text{up}} = 60 M_\odot \) and that a typical type II supernova ejects \( \sim 2 M_\odot \) of oxygen. This abundance can be regarded as the initial abundance of the disk, its value depending on when star-formation subsequently commenced in the disk (note that such two-epoch star-formation models have been advocated by, e.g., Chiappini, Matteucci & Gratton 1997). As can be seen from the figure this initial disk abundance is of the order \([O/H] \sim -2\). This is similar to the lowest abundance of the low-metallicity tail of the Galactic thick disk – see Beers & Sommer-Larsen (1995).

2.2. WARM DARK MATTER

Another, more radical way of solving the angular momentum problem is to abandon CDM altogether and assume instead that dark matter is “warm”. Such a rather dramatic measure not only proves very helpful in this respect, as will be discussed below, but may also be additionally motivated: Recently, various possible shortcomings of the CDM cosmological scenario in relation to structure formation on galactic scales have been discussed in the literature: 1) CDM possibly leads to the formation of too many small galaxies relative to what is observed, i.e. the missing satellites problem (e.g., Klypin et al. 1999). 2) Even if galactic winds due to star-bursts can significantly reduce the number of visible dwarf galaxies formed, sufficiently many of the small and tightly bound dark matter systems left behind can still survive to the present day in the dark matter halos of larger galaxies like the Milky Way to possibly destroy the large, central disks via gravitational heating, as discussed by Moore et al. (1999a). 3) The dark matter halos...
Figure 2. Face-on view of a disk galaxy with characteristic circular velocity $V_c \sim 300$ km/s formed in a warm dark matter simulation with no conversion of gas into stars (so the disk is purely gaseous). The mass of the disk is $M_{\text{disk}} \sim 2 \cdot 10^{11} M_\odot$ and its specific angular momentum is $j_{\text{disk}} \sim 2000$ kpc km/s.

produced in CDM cosmological simulations tend to have central cusps with $\rho_{\text{DM}}(r) \propto r^{-N}, N \sim 1 - 2$ (Dubinski & Carlberg 1991, Navarro et al. 1996, Fukushige & Makino 1997, Moore et al. 1998, Kravtsov et al. 1998, Gelato & Sommer-Larsen 1999). This is in disagreement with the flat, central dark matter density profiles (cores) inferred from observations of the kinematics of dwarf and low surface brightness galaxies (e.g., Burkert 1995, de Blok & McGaugh 1997, Kravtsov et al. 1998, Moore et al. 1999b, but see also van den Bosch et al. 1999).

The first two problems may possibly be overcome by invoking warm dark matter (WDM) instead of CDM: On mass scales less than the free-
streaming mass, \( M \lesssim M_{f,\text{WDM}} \), the growth of the initial density fluctuations in the Universe is suppressed relative to CDM due to relativistic free-streaming of the warm dark matter particles. In conventional WDM theory these become non-relativistic at redshifts \( z_{nr} \sim 10^6-10^7 \) for \( m_{\text{WDM}} \sim 1 \text{ keV} \), which is the characteristic WDM particle mass required to give sub-galactic to galactic free-streaming masses. As a consequence of this suppression, fewer low mass galaxies (or “satellites”) are formed cf., e.g., Moore et al. (1999a) and Sommer-Larsen & Dolgov (1999, SD99). The central cusps problem may be more generic (Huss et al. 1999 and Moore et al. 1999b), but WDM deserves further attention also on this point.

SD99 show that the angular momentum problem may be resolved by going from cold to warm dark matter, with characteristic free-streaming mass \( M_{f,\text{WDM}} \sim 10^{10}-10^{11} M_\odot \), and without having to invoke effects of stellar feedback processes at all. The reason why this kind of warm dark matter leads to a solution of the angular momentum problem is that because of the suppression of density fluctuations on sub-galactic scales relative to CDM the formation of a disk galaxy becomes a much more coherent and gentle process enabling the infalling, disk-forming gas to retain much more of its original angular momentum. In fact SD99 find it likely that the angular momentum problem can be completely resolved by going to the WDM structure formation scenario, which is more than can be said for the CDM+feedback approach so far. In Figure 2 we show a face-on view of a disk galaxy with characteristic circular velocity (where the rotation curve is approximately constant) \( V_c \sim 300 \text{ km/s} \) formed in a WDM simulation (in this simulation gas was not converted into stars). Clearly it is no longer a problem to form extended, high angular momentum disks in fully cosmological simulations. In comparison the extent of typical disks formed in “passive” CDM simulations (i.e. simulations not incorporating the effects of stellar feedback processes) is less than 1 kpc – see, e.g., Sommer-Larsen et al. (1999).

Unlike the CDM+feedback solution, one does not get a constraint on the early star-formation histories of the proto-galaxies, so no statements about the abundance of the first generation of disk stars can be made without further assumptions.

SD99 discuss possible physical candidates for WDM particles and find that the most promising are neutrinos with weaker or stronger interactions than normal, majorons (light pseudogoldstone bosons), or mirror or shadow world neutrinos.

3. The Tully-Fisher relation

In Figure 3 we show the cooled-out disk mass \( M_{\text{disk}} \) at redshift \( z=0 \) as a function of the characteristic circular velocity \( V_c \) of model galaxies formed in
Figure 3. The mass vs. characteristic circular velocity “Tully-Fisher” relation for the final disks formed in 16 WDM simulations of Sommer-Larsen & Dolgov (for \(H_0=70\) \(\text{km/s/Mpc}\)). Also shown is the observed \(I\)-band TF relation of Giovanelli et al. converted to mass assuming \((M/L_I)=0.25\) (dashed line), 0.5 (solid line) and 1.0 (dotted line) and \(H_0=70\) \(\text{km/s/Mpc}\). Finally, the symbol “MW” with errorbars shows the likely range of the total, baryonic mass and characteristic circular velocity of the Milky Way.

Our WDM simulations (assuming a Hubble parameter \(H_0=70\) \(\text{km/s/Mpc}\)). Also shown is the \(I\)-band Tully-Fisher (TF) relation of Giovanelli et al. (1997) converted to mass assuming \(I\)-band mass-to-light ratios \((M/L_I)=0.25, 0.5\) and 1.0 in solar units and \(H_0=70\) \(\text{km/s/Mpc}\). Finally, the baryonic mass of the Milky Way, estimated in a completely independent way, is shown (see SD99 for details). As can be seen from the figure we can match the slope of the TF relation very well assuming a constant \((M/L_I)\). To get the normalization right a \((M/L_I)\sim0.8\) is required. SD99 argue that this is quite a reasonable value in comparison with various dynamical and spec-
Figure 4. The temporal evolution of the average field strength in the disk for two values of $\langle \beta_0 \rangle$.

trophotometric estimates. Moreover, it is clearly gratifying that the Milky Way data point falls right on top of the theoretical as well as observational $M_{\text{disk}}$-$V_c$ relations (for $(M/L_I) \sim 0.8$, $H_0 = 70$ km/s/kpc).

Steinmetz & Navarro (1999) and Navarro & Steinmetz (1999) find a discrepancy between the observed and “theoretical” TF on the basis of CDM simulations of disk galaxy formation. It is hence possible that WDM helps out also on this point, but this has to be checked with more detailed simulations.

4. Magnetic fields in galactic disks and disk galaxy formation

Rögnvaldsson (1999) showed how the typical magnetic field strengths observed in galactic disks can be explained as a result of disk galaxy formation, as an alternative to the usually assumed dynamo amplification of an initially very weak magnetic field in the disk: Hot, virialized gas ($T \sim 2 \cdot 10^6$ K) in a dark matter halo is assumed to initially follow the dark matter distribution and to be rotating slowly, corresponding to a spin-parameter $\lambda \sim 0.05$, typical of galactic, dark matter halos. The hot gas is assumed to be threaded by a weak and random magnetic field. As the hot gas cools
radiatively, gravity forces it to flow inwards and due to the spin it forms a growing, cold, galactic disk in the central parts of the dark matter halo. The magnetic field follows the cooling gas inwards and is strongly amplified by compression and shear in the forming disk. Rögnvaldsson (1999) carried out magnetohydrodynamical (MHD) simulations of this process using an eulerian mesh MHD code. The simulations were run with various initial magnetic field strengths in the hot gas, parameterized by the initial ratio between the gas pressure and magnetic pressure $\langle \beta_0 \rangle = \frac{P_{gas}}{B^2/(8\pi)}$. The temporal evolution of the average magnetic field strength in the disk gas is shown in Figure 4. For weak initial fields ($\langle \beta_0 \rangle = 100-400$ was taken as a starting point, since these values are typical values in the hot, intergalactic gas in clusters of galaxies) the average magnetic field strength grows gradually from about $t=1$ Gyr (after an initial relaxation phase). The average values of 1-2$\mu$G reached after about 5 Gyr are quite reasonable for typical disk galaxies, indicating a route to the explanation of the magnetic field strengths observed in galactic disks alternative to the usual dynamo one.

Another aspect of the growth of the field strength is reflected in the radial average in the disk, shown in Figure 5 at various times for a simulation
with $\langle \beta_0 \rangle = 400$. The field strength is always highest in the outermost part of the growing disk, since the fieldlines brought in with the cooling flow are stacked on top of the already existing field there and the field is further amplified by the disk shear.

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