A WAY OUT OF THE DISK ANGULAR MOMENTUM CATASTROPHE IN HIERARCHICAL HYDRODYNAMICAL SIMULATIONS

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Abstract

We present results that suggest that DAMCs plaguing hierarchical hydrodynamical simulations of galaxy formation, not including star formation processes, are due to the inward gas transport that follows bar disk instabilities triggered by interactions and mergers. They also show that DAMCs can be easily avoided by including star-forming processes, as they lead unavoidably to the formation of compact stellar bulges that stabilize disks against bars. The formation of disks similar to those observed demands, in addition, that not all the gas is depleted into stars at high $z$, so that they can be formed at lower $z$.

1 Disk Formation in Hierarchical Hydrodynamical Simulations

According to Fall and Efstathiou’s (FE) standard model of disk formation [8], extended disks similar to those observed in spiral galaxies can be formed from the diffuse halo gas component provided that gas conserves its specific angular momentum ($j$) during collapse. However, so far, no hydrodynamical simulation of galaxy formation in fully consistent hierarchical cosmological scenarios had been able to produce extended disks similar to observed spirals. The problem was either the excessive loss of angular momentum by the gas clumps as they merge inside the dark haloes, when no star formation processes are considered, resulting in too concentrated disks (i.e., the so-called disk angular momentum catastrophe problem, hereafter DAMC [10] [11] [18] and references quoted therein), or the too early gas exhaustion into stars as it cools and collapses, leaving no gas to form disks at low $z$ [4] [12]. In this paper we report on some results of disk formation in hierarchical hydrodynamical simulations [14] [13] where a simple implementation of star formation that prevents gas depletion at high redshifts, but permits the formation of stellar bulges, has allowed extended and populated disks to form at later times. We have followed the evolution of $64^3$ particles in a periodic box of 10 Mpc ($H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$) using a SPH code coupled to the high resolution AP3M code [13], either including a star formation algorithm with star formation efficiency $c = 0.01$ (S1 simulation) or not (S2 simulation). The initial distribution of positions and velocities is the same in both S1 and S2, and is consistent with a standard flat CDM cosmology, with $\Omega_b = 0.1, \Lambda = 0$ and $b = 2.5$. All, dark, gas and star particles have the same mass, $M = 2.6 \times 10^8 M_\odot$. The gravitational softening length is 3 kpc and the minimum allowed smoothing length is 1.5 kpc. Baryonic
objects forming disk-like structures (DLOs) identified in S1 have stellar bulge-like cores and extended, populated disks, their masses and specific angular momenta are compatible with those of observed spirals, and their bulge and disk scales, $R_b$ and $R_d$, respectively, are also consistent with their observable values. In S2, DLOs have an inner, rather disordered gas concentration and, also, extended disks, but much less populated than their S1 counterparts. Gas particles inside their optical radii have too low $j_z$, and their bulge and disk scales disagree with observations (see Table 1 and [7] [5] [6]).

Table 1. Some Characteristics of DLOs with $N_{\text{baryon}} > 150.$

| DLO | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|-----|----|----|----|----|----|----|----|----|----|----|
| $N_{\text{gas}}$ | 348 | 359 | 307 | 311 | 210 | 151 | 227 | 189 | 108 | 109 |
| $N_{\text{star}}$ | 278 | 240 | 211 | 215 | 95  | 69  | 79  | 157 | 99  | 47  |
| $R_b$ (S1, kpc) | 0.74 | 0.74 | 0.85 | 0.74 | 0.54 | 0.53 | 0.99 | 0.49 | 0.54 | 0.40 |
| $R_b$ (S2, kpc) | 1.29 | 1.29 | 1.41 | 1.19 | 1.27 | 1.32 | 1.47 | 1.23 |
| $R_d$ (S1, kpc) | 7.33 | 5.66 | 10.90 | 9.98 | 6.50 | 5.61 | 6.56 | 5.29 | 7.07 | 9.75 |
| $R_d$ (S2, kpc) | 6.99 | 7.08 | 14.04 | 9.02 | 5.87 | 5.62 | 13.31 | 10.75 |

So, stellar bulges seem to be critical to ensure global angular momentum conservation in the assembly of disks in hierarchical hydrodynamical cosmological simulations. In fact, it is known that bulges play a fundamental role in stabilizing disks against the bar instability mode, that, otherwise, would cause a strong inward material transport due to angular momentum losses [4] [9] [17]. To clarify their role, we briefly describe how disks are assembled in S1 and S2 simulations [14] [6]. i) First, dark matter haloes collapse at high $z$ forming a first generation of (very small) disks and stars. ii) Then, the first un-stabilizing mergers at high $z$ happen, resulting in disk disruption and rapid mass inflow to the central regions with angular momentum loss and violent star formation, mainly at the central regions. Also, most preexisting stars will concentrate at the center of the new object through violent relaxation. These two processes help build up a central stellar bulge-like structure. iii) After the first mergers, a disk is regenerated through an infall of gas particles, either belonging to the baryonic merging clumps or diffuse. For example, a compact stellar bulge and an almost cold disk in DLO #1 of S1 at $z = 0.57$ are apparent in Figure 1a. iv) After disk regeneration, the system can undergo new major merger events at lower $z$. During the orbital decay phase, previous to the actual fusion of the DLOs, most of their orbital angular momentum is transported to (the particle components of) each host halo, spinning it up (as in [1] [2]). Because, now, the disks involved in the merger are stabilized by their bulges, no strong gas inflow occurs in this phase (as in [6]). As the disks approach one another, they are heated and finally disrupted, but the high efficiency of gas shocking and cooling, and the symmetry of the central potential, quickly puts those of their gas particles with high angular momentum into a new intermediate disk, while their low angular momentum particles sink to the center where most of them are transformed into stars, feeding the bulge. The stellar bulge of the smaller DLO is eventually destroyed and incomplete orbital angular momentum loss puts most of its stars on the remnant disk (Fig. 1b, note incomplete relaxation). v) Relaxation and disk regeneration are completed. Most of disk external particles are supplied by infall, as in iii) (Fig. 1c).

Note in Fig. 1c that at $z = 0$ most gas particles placed at $R_i \approx 30$ kpc have $j_{z,i} \approx |\vec{j}_i| \approx v_c(R_i) R_i$, where $v_c(R) = GM(< R)/R$, with a small dispersion around this value, that is, they follow circular trajectories on the equatorial plane, forming a cold thin disk. In contrast, those at $R_i > 30$ kpc (halo gas particles) are disordered, with their $|j_{z,i}|$ taking any value under the full line. Roughly half of them are in counterrotation (i.e., with $j_{z,i} < 0$). The specific angular
Figure 1: Specific angular momentum component along \( \vec{J}_{\text{dis}} \) for each baryon particle of halo \#1, versus their positions at different \( z \). Points: gas particles, stars: stellar particles; open symbols: counterrotating particles. Left panels: S1 version at different \( z \); right panels: S2 version at approximately the same \( z \). Full lines: \( v_c(R)R \); dotted lines: \( X_2(R) \) for actual disks at each \( z \); dashed line: \( X_2(R) \) for the pure exponential version at \( z = 0 \). Arrows mark \( R_{\text{ad}} \) and \( R_{\text{ped}} \), where \( X_2(R) = 3 \).

momentum of halo gas particles, however, is the same as that of gas disk particles, and, also, the same as that of dark matter particles. Stars at \( R_i \lesssim 2 \) kpc form a compact central relaxed core, with \( \vec{J}_i \) without any preferred direction and very low \( |\vec{J}_i| \) (that is, they have been formed from gas particles that had lost much of their \( |\vec{J}_i| \)), while those at \( R_i \gtrsim 2 \) kpc roughly follow a (thicker) disk.

The assembly of galactic-like objects in S2 follows the same stages. We recall that in both simulations, haloes and merger trees are identical. The main difference is that in S2, the i) and ii) stages do not result in a stellar core, and, consequently, in iii) stage an unstable gas disk is formed, susceptible to grow bars. In particular, during the orbital decay phase in iv), strong gas inflow and \( j \) loss are induced (i.e., a DAMC, see also Fig. 1d, and [9]). The actual fusion completes the gas inflow (Fig. 1e), involving most of the gas particles originally in the merging disks. Few of them are left for disk regeneration, so that, in phase v), new disks are formed almost only from halo gas particles (Fig. 1f), and hence their low population.

The behaviour patterns described so far are common to the other DLOs in S1 or S2. In any case, particles in the external cold disk component at \( z = 0 \) have fallen in the quiescent phase of evolution that follows the last major merger event, according with FE’s scenario, while most of those in the central regions (in S2), or those giving rise to stars in the bulge (in S1) have been involved in a DAMC. Most particles in the intermediate disk component in S1 DLOs belonged to
the merging objects and have suffered a partial angular momentum conservation in the merger event. Hence, cold thin disks naturally appear in the non-violent phases of evolution. However, as stated, cold disks are strongly unstable against the bar mode. Some works on disk stability ([4] [17] and references therein) suggest that sometimes a central bulge is needed to ensure stability, as massive dark haloes are not always able to stabilize a given amount of baryons as pure exponential disks (ped). This could be the process at work in DAMCs observed in hydrodynamical simulations. To find out whether this is the case here, we have calculated the $X_2(R)$ parameter [6] [8] for the disk component of our DLOs at different $z$ (Fig. 1), and, also, for their ped versions (i.e., putting all their respective baryonic masses distributed as a ped).

Recalling the $X_2(R)$ stability criterion, if we define the stability thresholds, $R_{\text{ad}}^{\text{st}}$ and $R_{\text{ped}}^{\text{st}}$, as the points where $X_2(R) = 3$ for actual and pure exponential disks, respectively, it is apparent from Fig. 1 that disks, when present, are stable: they are detected at $R > R_{\text{ad}}^{\text{st}}$ if they have had enough time to form after the last merger. By contrast, the ped version of DLO #1 at $z = 0$ would be stable only at larger $R (R > R_{\text{ped}}^{\text{st}} \simeq 21 \text{ kpc})$. This behaviour is common to any DLO in S1 or S2, and so central mass concentrations are needed to stabilize these disks. These results strongly suggest that DAMCs result from strong gas inflows due to disk instabilities triggered by interactions and mergers during the assembly of galaxy-like objects, and that they can be easily avoided by stabilizing the disks with stellar bulges.

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