GALAXY FORMATION WITH SPH

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Cosmology and Hydrodynamics with Gasoline

(Stadel 2001; Wadsley, Stadel & Quinn 2003)

Conspirators:

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Multi Platform, Massively Parallel treecode + SPH, multi stepping, cooling, UV background, Star Formation, SN feedback.
Santa Barbara tested...
Is the formation of a realistic disk galaxy possible in a LCDM Universe?

A “minimal” realistic disk galaxy:

- disk dominated (B/D < 0.3)
- the disk is large enough for its luminosity
- sits on the Tully-Fisher relation (coupling between baryons and dark matter)
- different components are present, e.g. a thin and a thick disk (see Dalcanton et al. 2003)
Angular momentum problem

Disks are too small in cold dark matter simulations with SPH hydrodynamics (Navarro & Benz 1991, Navarro & White 1994). Progenitor lumps cool efficiently and lose angular momentum due to dynamical friction – the final galaxies are made of material with too low angular momentum compared to observations (Navarro & Steinmetz 2000; Steinmetz & Navarro 1999, 2002).

“Physical” solutions: strong energetic feedback (UV, supernovae, AGNs) to keep gas hotter and reduce angular momentum loss of lumps (Thacker & Couchman 2000, 2001; Abadi et al. 2003) or truncate power spectrum (Sommer-Larsen & Dolgov 2001). Feedback already required to avoid overcooling problem (White & Frenk 1991).
Are we sure we can trust the hydro simulations?

Several numerical effects can affect disk formation;

- **Two body heating** (Moore et al. 1996, Steinmetz & White 1997) ---> turns dynamically “cold” particles into dynamically “hot” particles, or disks into bulges!
- **artificial viscosity** ---> induces artificial losses of angular momentum of the gas component (Thacker et al. 2000)
- **Hydrodynamical torques** --> standard SPH does not solve for the multi-phase structure of the ISM, artificial pressure gradients can arise at the interface between a cold disk and surrounding hot gas and produce loss of J among cold particles (Okamoto et al. 2003)

*All these effects depend on resolution!*
High resolution galaxy formation

(Governato, Mayer et al, 2003)

Renormalization Technique: 1kpc spatial resolution in a 100Mpc Box

Total Mass $2.9 \times 10^{12} \, M_\odot$

Virial Radius 375Kpc

$N_{\text{gas}} (R < R_{\text{vir}}) \sim 200,000$

$N_{\text{dark}} (R < R_{\text{vir}}) \sim 100,000$

Spin Parameter $\lambda = 0.035$

$V_{\text{vir}} = 185 \, \text{Km/sec}$

$C = 13.6$ (Mean: 13.2)

Formation time $z = 0.75$

($>50\%$ of $z=0$ mass)

Last major merger $z = 2.5$
Physics included

• Compton and radiative cooling for a gas of primordial composition

• Star formation (Katz 1992) – gas particles spawn stars with Miller-Scalo stellar mass function

• Explosions of supernovae type I and II - a fraction of the energy is transferred to the gas only as thermal energy (thermal feedback) --> this is the 'mildest' among the possible recipes for feedback (see Springel & Hernquist 2002; Thacker & Couchman 2001).

• Heating by a uniform cosmic UV background – kicks in at $z = 6$ (Haardt & Madau 1996).
Dark Matter Distributions

(1Mpc per side)

LCDM

LWDM 2 keV particle
The formation of a LCDM Disk Galaxy:
Governato, Mayer et al. 2003

The Movies.

Assembling of the stellar component  Age of the disk component
The LCDM galaxy at $z=0$

Age < 10 Gyr

Disk (+ bar)

Age > 10 Gyr

Bulge + Stellar Halo

Stellar ages are shown (brighter colors for younger ages) boxes are 40 kpc
The LWDM galaxy at z=0

Age < 10 Gyr

Disk (+ bar)

Age > 10 Gyr

Bulge + Stellar Halo

Stellar ages are shown, boxes are 40 kpc

LWDM galaxy has a more prominent, thinner and higher \( \nu/\sigma \) disk, but only 20% more extended
Profiles steeper than that of M31 at the center due to low angular momentum spheroid (this happens also with stronger feedback in Abadi et al. 2003).

- LCDM disk kin. hotter due to heating by satellites
Stellar surface density

LCDM: $R_h \approx 3\,\text{kpc}$
$R(\text{bulge + bar}) \approx 1\,\text{kpc}$

LWDM: $R_h = 3.6\,\text{kpc}$
$R(\text{bulge + bar}) \approx 1\,\text{kpc}$

From Mo, Mao & White (1998) model (cons. of specific angular momentum + ad. contraction) one gets 3.4 kpc (LCDM)
Disk angular momentum

J/M (disk) \~ 0.5 J/M (dark) -- LCDM
J/M (disk) \~ 0.9 J/M (dark) -- LWDM

Disk built by smooth accretion of gas with J/M higher than that of the dm halo after last major merger (Chen et al. 2003; Van den Bosch et al. 2002).

Blue dot = LCDM run (disk only)
Red dot = LCDM run (disk + spheroid)
B&W data points from Thacker & Couchman (2001)
Angular momentum of galaxy including spheroid (formed in last major merger) significantly lower
Lower J in the LCDM galaxy vs. LWDM (at same resolution) suggests that losses of J by progenitor lumps is important (but two-body heating not necessarily the same in both runs, see Diemand et al. 2003). However J decreases in both runs, which leaves room for numerical effects even at this resolution.

A cosmological-hydro simulation is extremely complex - hard to disentangle numerical effects.

Better resort to simple tests:

The rotating cooling gas cloud (Navarro & White 1994; Thacker et al. 2000; Okamoto et al. 2003) using up to millions of particles to test numerical angular momentum losses (Kaufmann, Mayer, Moore & Stadel, in prep.)
Initial Conditions

MW-sized halos (c=10, Vvir ~ 150 km/s), gas is 10% of mass. No star form./feedback/UV, use temp. floor (Tmin 30000/60000 K). Several simulations spanning more than an order of magnitude in mass resolution and with different gravitational softenings. Highest res. runs (above) is 500,000 gas particles and 1 million dark particles (more than ten times higher than in Okamoto et al. 2003)
Convergence tests: mass and $J$

RUN1 $N_{\text{gas}}=30.000$, $N_{\text{dark}}=30.000$ (green)
RUN2 $N_{\text{gas}}=100.000$, $N_{\text{dark}}=30.000$ (magenta);
RUN3 $N_{\text{gas}}=100.000$, $N_{\text{dark}}=100.000$ (black);
RUN4 $N_{\text{gas}}=100.000$, $N_{\text{dark}}=100.000$ no shear reduced viscosity (blue)
RUN5 $N_{\text{gas}}=500.000$, $N_{\text{dark}}=1$ million (red)

“Correct” evolution of $J/M$ requires 100.000+ particles
At high resolution collapsing gas loses only ~ 10% of its angular momentum. Hot particles (T > Tdisk) in the same shell gain angular momentum. Spurious hydrodynamical torques between cold and hot gas due to SPH inability to resolve a two phase medium might be responsible (Okamoto et al. 2003; Marri & White 2002).
Morphological evolution

NGas = 100,000
Ndark = 100,000
T = 2 Gyr

NGas = 500,000
Ndark = 1 million
T = 4.5 Gyr

Stronger grav. instability
At higher res.!
Conclusions

-A stellar disk with a realistic size and angular momentum can form in a LCDM cosmology even with minimal feedback if resolution is high enough.

-Quiescent merger history after z=1 with late smooth infall of high angular momentum gas crucial for disk formation.

-Remaining problem is the massive, old spheroid that lowers the global angular momentum of the galaxy below that of typical spirals and steepens the rotation curve too much.

-A “warm” spectrum does not improve significantly on the spheroid issue (B/D only slightly lower). Reduced accretion and heating by satellites however yields a colder and thinner disk.

-Tests show that > 100,000 gas and dark particles are needed to avoid strong numerical loss of angular momentum. In all existing simulations resolution is much lower in early progenitors that produce the old spheroid.

-Early (z>6) strong feedback/heating might help but it is not necessarily the solution to galaxy formation. Resolution comes first!
LWDM GALAXY
The Galaxy in Detail

B/D = 0.32
Rh = 3Kpc
Mdisk = 9e10
Mstar = 2.e11
Mgas = 1.36e11
Baryon fr = 0.13
Xray = 10**42 erg/sec
Tem = 0.38keV
Jdisk = 0.75Jh

Small angular momentum loss
Two-body heating from dark particles: tests with equilibrium galaxy models

Models reproduce the structure of the galaxy at $z=0.6$, just before the bar instability. Vary $N_{\text{dark}}, N_{\text{gas}}, N_{\text{star}}$

All go bar unstable (explains loss of $J$ in inner disk) and a disk structure remains only if at least 100,000 dark particles are used.

Above: decrease of $J$ (baryons) over 6 Gyr of evolution
WLDM vs LCDM

R=150 kpc, z=0

Disk in WLDM is larger, smaller B/D and fewer satellites
Star formation: cold vs. warm MW

[Graph showing SFR (M$_\odot$/yr) vs. $\tau$ (Gyr) for LCDM and LWDM models, with arrows indicating $z=3$ and $z=4$]
Stellar disk kinematics

**LCMCD disk** (age < 10 Gyr)  **LWDM disk** (age < 10 Gyr)

LWDM disk has a maximum $v/\sigma$ a factor of 2 higher.
Collisions and impulsive heating by satellites are responsible for the higher velocity dispersion in LCDM disk.
The Making of a Galaxy

By The N-body Shop
Lucio Mayer, Fabio Governato, James Wadsley, Jeff Gardner, Thomas Quinn  *(UW, UPittsburgh, McMaster)*

Use N-body simulations to follow the formation of a massive disk galaxy, its stellar component and its system of satellites

With sufficient numerical resolution to:
- avoid major numerical pitfalls
- adequately resolve the structure of the stellar disk
- allow quantitative comparison with observations.
WARM vs. COLD DARK MATTER

Possible Benefits of reducing fluctuations at SUB Galactic Scales:

Central Cusps erased?

Overcooling Reduced -> less cold baryons

Number of satellites drastically reduced

Reduce low angular momentum gas

Reduced substructure -> reduced Disk Heating

Constraints from: Lyman Limit Systems

Mass of warm candidate > 2keV
The Vitals

- Total Mass 2.9e12Mo
- Virial Radius 375Kpc
- Spin Parameter $\lambda = 0.035$
- $V_{\text{vir}}$ 185 Km/sec
- $C = 13.6$ (Mean: 13.2)
- Formation time $z = 0.75$ (50% $z=0$ mass)
- Last major merger $z=3$ (see Frenk et al. 1988)
The angular momentum "catastrophe"

Semi-analytical models of disk formation (Mo, Mao & White 1998; Fall & Efstathiou 1982): correct disk sizes by assuming 1) baryons have same initial specific angular momentum distribution of DM and 2) angular momentum is conserved during collapse of baryons inside halos.

Numerical simulations: disks sizes would be correct if they had same spec. angular momentum of dark halos 1) and 2) the higher the mass scale, the lower the angular momentum of halos: cause is the transfer of angular momentum from the baryons to the halo, larger if number of mergers higher ===>disks are too small!

Navarro & Benz 1991
Tests that we are conducting in isolated, equilibrium disk galaxy models: transfer of angular momentum occurs and strongly depends on the gas resolution. Loss of J more than doubles reducing the resolution by a factor of 4.

Tests performed by L. Ma using the parallel binary N-Body/SPH code "GASOLINE" (Wadsley, Quinn & Stadel 2002). Red=5000 gas particles White=20,000 gas particles Halo + stars ~ 200,000 particles.
Energetic feedback (e.g. by supernovae) should heat/expel the gas in small progenitor halos at high z—→ more gas is in a diffuse phase as opposed to tightly bound baryonic cores when it falls onto the main progenitor at low z —→ loss of angular momentum reduced and resulting disks larger (Navarro & Steinmetz 1999, 2000, 2001).

Recent simulations of galaxy formation with > 10 times resolution ( ~ 100,000 gas + DM particles within the virial radius) and strong (turbulent) feedback obtain much larger disks - still only S0-type galaxies are obtained, no Milky Way look-alike (Thacker & Couchman 2000, 2001). For same star formation/feedback algorithm results better at high resolution because objects form earlier and gas is heated sooner (Thacker & Couchman 2001).

Low gas resolution in SPH simulations can affect the angular momentum problem also through artificial viscosity; viscosity at low resolution is large (e.g. Hernquist & Katz 1989) —→ can cause additional loss of angular momentum for the gas that has already settled into a disk.
Morphology and resolution

Stellar component in a dwarf galaxy at $z=2$

$N_{\text{gas}} = 20,000$

$N_{\text{gas}} = 3,000$
The Galaxy in Detail

B/D = 0.32
Rh = 3 Kpc
Mdisk = 9e10
Mstar = 2e11
Mgas = 1.36e11
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Small angular momentum loss
Ages of disk stars

[Graph showing ages of disk stars across different radii, with curves labeled LCDM and LWDM.]
Making galaxies in a CDM Universe

Lucio Mayer
University of Zurich/University of Washington

LG simulation by Ben Moore and the N-Body shop
Q Toomre's local instability parameter

\[ Q = \frac{\kappa \sigma}{3.36 \Sigma G} \]

Large Q induced by tidal interactions
Galaxy formation in a CDM Universe

- Most of the matter in the Universe is cold dark matter (CDM). CDM particles have negligible thermal motion and interact only gravitationally.

- Initial small perturbations of the density field are amplified by gravitational instability: structure formation proceeds in a bottom-up fashion, from dwarf galaxy halos up to halos of galaxy clusters.

- Dark matter halos provide the potential wells where baryons subsequently cool and collapse, forming visible galaxies.

==> BIG UNCERTAINTIES, e.g. STAR FORMATION AND FEEDBACK
The Tully-Fisher problem

1) For a given $M_{\text{star}}$ the ratio $V_{\text{rot}}/V_c$ is much larger than required by observed TF. OR- at a fixed rotation speed galaxies are too faint by about 2 magnitudes.

2) Cause might be either too much dark matter (but see Klypin et al. 2002) or too concentrated baryonic components = disks of galaxies have too little angular momentum.

Navarro & Steinmetz 2000
What happens to the circular velocity of halos as baryons collapse into a rotationally supported disk......(Navarro & Steinmetz 1999)

Even allowing for a factor of 2 variation in the concentration of halos does not solve the problem (see vertical error bars)
Angular Momentum Loss

Angular momentum loss within 15 Kpc

Cumulative effects of resolution and encounters with satellites

Note: artificial viscosity effects only in gas
Angular Momentum Transfer
Hot Gas
Star Formation: effects of resolution

SFR higher in lower resolution run.

Most likely due to larger gas angular momentum loss and inflow.
Warm Dark Matter: Eg. Sterile Neutrinos (Shi & Fuller)
- Non-Equilibrium, Resonant Formation \( N_s \ll 1 \)
- Multiple Masses fairly natural
- Supernova \( m > 1 \) keV
- Current velocity dispersions < 1 km/s (Dwarf Galaxy cores?)
SPH codes solve the fluid equations using a lagrangian approach: the values of the hydrodynamical variables are carried by particles with a given mass that represent fluid elements. The hydrodynamical variables are calculated interpolating over a given number of neighboring particles (Monaghan 1979, 1981). Gravity is usually solved using a tree algorithm that also requires a smoothed evaluation of the force plus forces from distant particles are calculated by grouping them together and expanding in multipoles.

\[ f_{i}^{\text{smoothed}} = \sum_{j=1}^{n} f_{j} A_{ij} W_{ij} (\vec{r}_{i} - \vec{r}_{j}, h_{i}, h_{j}) \]

\[ \rho_{i} = \sum_{j=1}^{n} m_{j} W_{ij} \]

\[ W = \frac{1}{2} W (|\vec{r}_{i} - \vec{r}_{j}|/h_{i}) + \frac{1}{2} W (|\vec{r}_{i} - \vec{r}_{j}|/h_{j}). \]

Momentum equation (for \( \Phi g = 0 \))

\[ \frac{d\vec{v}_{i}}{dt} = -\sum_{j=1}^{n} m_{j} \left( \frac{P_{i}}{\rho_{i}^{2}} + \frac{P_{j}}{\rho_{j}^{2}} + \Pi_{ij} \right) \nabla_{i} W_{ij} \]
Artificial "Monaghan" viscosity (Monaghan 1992)

\[
\Pi_{ij} = \begin{cases} 
-\alpha \frac{1}{2} (e_i + e_j) \mu_{ij} + \beta \mu_{ij}^2 
& \text{for } \vec{v}_{ij} \cdot \vec{r}_{ij} < 0, \\
0 
& \text{otherwise}, 
\end{cases} 
\]

where \( \mu_{ij} = \frac{h (\vec{v}_{ij} \cdot \vec{r}_{ij})}{\vec{r}_{ij}^2 + 0.0025 (h_i + h_j)^2} \)

Balsara switch multiplies coefficients to avoid spurious dissipation in shear flows (Balsara 1995)

Mass resolution is fixed by the mass assigned to particles, force resolution for gravity by the softening length, for hydro limited by a minimum smoothing length but adjustes to local density.

No limitation in the volume of the system (no outer boundary necessary).

Artificial viscosity is necessary to avoid interpenetration of particles and guarantee stability of the computations. It dissipates kinetic energy into heat: real shock dissipation occurs over a few mean free path length of the molecules, several order of magnitudes below the scales resolved by particles (> 100,000 km!). Artificial viscosity decreases with resolution (depends on \( h \)). Excessive dissipation at low resolution could damp instabilities (Boss 2001), on the other end once unstable regions are formed artificial clumping might result if particles are too massive (Nelson et al. 2000a)
The Tully Fisher relation.

In CDM models: "virial" velocity of halo $V_c = (GM_v/R_v)^{1/2}$ related to virial mass $M_v$

$\Rightarrow M_v \sim V_c^{3}$

$R_v$ must be such that, for a given enclosed $M_v$, the mean density of the halo is roughly 200 times the mean density of the Universe at the halo formation epoch, very weak dependence on cosmology (Eke et al. 1996, 1998)

The I band Tully-Fisher relation has the same slope:

$L_I \sim V_{rot}^{3}$ (Giovanelli et al. 1997) $\Rightarrow$ cosmological origin?

Does the TF reflects corresponding scaling relations in DM halos?

If answer is yes ($\Rightarrow$ coupling TF and $M_v$-$V_c$ relation):

$F_{md} = M_d/M_v \sim (M_d/L_I) \times (V_{rot}/V_c)^{3}$ (Navarro & Steinmetz 2000).
The simplest situation: all the numbers in correlation are the same for every galaxy (e.g. Mo et al. 1998) In general any combination that fits the above correlation will also fit the TF.

The disk mass-to-light ratio in disk galaxies may not be a constant ==> LSB and dwarf galaxies appear to be less efficient in converting baryons into stars (McGaugh 2000).

**Important:** compare observed Vrot must be the rotational velocity measured at the optical radius (~ 3 rh) and not with virial velocity of the halo! (which is smaller in a typical NFW profile....)

Rotationally supported disks form inside halos in N-Body simulations with hydrodynamics but......these reproduce only the slope, not the zero-point of the observed TF. Numerical scatter is three times smaller than observed one because changes in fmd and Vrot/Vc are correlated ==> scatter is along the TF.
Both problems can in principle be solved by increasing feedback efficiency. Feedback can restrain star formation in smaller-high $z$ halos (that have $t_c << t_d$) avoiding the formation of dense baryonic lumps for the same luminosity disks larger and rotational velocities lower.

Navarro & Steinmetz (2000): extreme "kinetic" feedback but rotational velocities are poorly affected and only in halos with $V_c < 100$ km/s......

$\Rightarrow$ TF zero point even worse, galaxies even fainter at fixed $V_{rot}$!
Increase further feedback?! $\Rightarrow$ star formation efficiency at low redshift may be substantially lower than predicted by the Kennicutt law (Kennicutt 1998).

Two alternatives:
- lower mass-to-light ratios for disks ($M/L= 0.3-0.4$ instead of 2.5) or
- lower ($\sim 3-5$) concentrations for the halos.

First alternative would require changing spectrophotometric evolution of stars or initial mass function (!), second that CDM has a serious failure......
The angular momentum "catastrophe"

Semi-analytical models of disk formation (Mo et al. 1997, 1998): correct disk sizes by assuming 1) baryons have initial specific angular momentum comparable DM and 2) angular momentum is largely conserved during collapse of baryons inside halos.

Numerical simulations: disks are too small! Bulge/Disk $\sim 0.5-1$

Thacker & Couchman 2001

DM within $R_{\text{vir}}$

15,000 particles

very high $J$ halo