Disk Galaxy Formation in a Cold Dark Matter Universe: A Test of the Paradigm

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The Paradigm

- Structure in the Universe originates from quantum fluctuations in the early universe that grew through a period of inflation and were subsequently amplified by gravity.
Our motion through the universe

Dust in our own Galaxy

Fluctuations in the photon-baryon fluid at $z \sim 1000$ (1 part in $10^5$)
The Large Scale Structure of the Universe

The APM galaxy survey
How do we get from the smooth universe of yesteryear to the highly structured universe of today?

**Answer: Gravitational Instability**

- Overdense regions get more and more overdense as the universe expands.
- Underdense regions get more and more underdense as the universe expands.

We can try and simulate this...
Hierarchical Structure Formation

Need (non-baryonic) dark matter!

Courtesy of The Virgo Collaboration
The “Concordance” Model

• The geometry of the Universe is flat ($\Omega_{\text{tot}}=1$).

• Ordinary matter (baryons) contribute less than about 4% ($\Omega_b\sim0.04$) of the energy density required for this. (Big Bang nucleosynthesis)

• ‘Dark’ matter contributes about 30% ($\Omega_M\sim0.3$). This dark matter is contributed by some WIMP, and behaves as a cold, collisionless fluid.

• The other 70% ($\Omega_\Lambda\sim0.7$) comes from a cosmological constant-like contribution. (SNIa)

• The universal expansion rate is

  \[ \sim 65 \pm 10 \text{ km/s/Mpc} \]
Successes of the Concordance Model

By matching these observations to the model...

- The world geometry inferred from SNIa and CMB measurements
- The extragalactic distance scale
- The primordial abundance of the light elements
- The amplitude of the CMB fluctuations

We can understand all this...

- The age of the universe
- The baryonic mass fraction of galaxy clusters
- The present-day abundance of massive galaxy clusters
- The shape and amplitude of galaxy clustering patterns
- The magnitude of large-scale coherent motions of galaxies
- Etc..
One example...

Note that the successes of the model are on scales > 1 Mpc or so!

Wu, Lahav & Rees 1999
So the large scale structure seems OK, how about smaller scales?
**Disk galaxies: probes of the small scale structure of the Universe**

- Disk galaxies are thin, dynamically cold (fragile!) stellar systems supported by rotational motions.
- They are the most common type of galaxy in the Universe.

**Say no to spheroids!**

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The formation of a galaxy-sized CDM halo

- A substantial fraction of the mass is accreted through mergers.
- Lots of satellites ("substructure") remain at the present day.
- Not an easy environment for the formation of disk galaxies!

Steinmetz & Navarro 2000
Hierarchical Galaxy Formation

Galaxies form by the collapse of baryons within dark halos.

Baryons dissipate energy through radiation and settle into centrifugally supported disks.

Steinmetz & Navarro 1997
Disk Galaxies within Dark Halos

Steinmetz & Navarro 1997
Potential Problems for CDM (I):

- Cold Dark Matter halos are “cuspy”: i.e. the density increases monotonically towards the center. (At odds with rotation curves of low surface brightness galaxies?)
Potential Problems for CDM (II):

- CDM galaxy halos possess large amounts of “substructure”; several hundred satellites with circular velocities > 10 km/s. (At odds with the relatively few known satellite companions of the Milky Way?)

Moore et al 1999
Klypin et al 1999
Potential Problems for CDM (III):

- Cold Dark Matter halos are assembled through a sequence of merger events. (At odds with the angular momentum and thinness of stellar disks?)

Steinmetz & Navarro 1999
Are these fatal problems for CDM?

At least some theorists seem to think so. This has led to some radical proposals:

• Self-interacting dark matter
• Warm dark matter
• Self-interacting warm dark matter
• ‘Fuzzy’ dark matter
• Other combinations of the above…

How does this help? For example...
Warm vs Cold Dark Matter

Cold vs Warm Dark Matter
Density Profiles: Cold vs Warm Dark Matter
The end of the paradigm?

• Before abandoning the paradigm, it seems appropriate to scrutinize the problems in more detail...
Simulations and analytical arguments show that the dark matter density increases systematically towards the center (the halo has a ‘cusp’).

Rotation curves of low surface brightness galaxies seem to show that the dark halo has a constant density ‘core’ rather than a ‘cusp’ at the center.
Most disk galaxy rotation curves are consistent with “cuspy” CDM halos.

Fig. 2.—Rotation curve fits using the NFW and the ISO halo models shown for a high-surface brightness galaxy (NGC 3198, de Blok 1998) and a low-surface brightness galaxy (F563-1, de Blok 1997). Note that either halo model produces acceptable fits, although they may require different contributions of the disk.

NFW + ISOTHERMAL DO NOT EQUALLY WELL EXCEPT FOR A FEW LSBs
Rotation curve vs CDM predictions for a Low Surface Brightness (LSB) galaxy

LSB galaxies are dominated by dark matter

McGaugh & de Block 1998
see also Moore 1994
Flores & Primack 1994
Beam smearing?

See also van den Bosch et al 2000

Rotation Speed in km/s

LSB galaxies

H I — de Blok et al (1996)
Ha — Swaters et al (2000)

F563-V2
F568-1
F568-3
F568-V1
F574-1

Radius in arcsec
Dwarf LSBs also show the same problem...

The end of Cold Dark Matter or just a few rogue galaxies?
A rogue?

Radius in kpc

Rotation Speed in km/s
The cuspy dark halo of DDO154

DDO 154

(Original HI data from Carignan & Purton, 1999)
Summary and Conclusions

- Gaseous disks generally resembling spiral galaxies are produced through dissipative infall of baryons within dark matter halos.

- Disk galaxy rotation curves, including those of LSBs and dwarf galaxies, are consistent with the “cuspy” dark halos predicted in CDM scenarios.
Summary and Conclusions (II)

- The currently favourite cosmological model ($\Lambda$CDM), however, fails to reproduce:
  - angular momentum (or size) of observed disks
  - Feedback from stellar evolution or active nuclei?
  - substructure and satellite numbers (?)
  - Lack of correspondence between stellar and halo velocities?
- Although options are certainly being considered, the evidence for a failure of the paradigm on galactic scales is less than overwhelming.
The End
The halo of a CDM galaxy cluster

Moore et al 1999
Cuspy Cold Dark Matter halos

- Mass profiles of dark halos are independent of halo mass and cosmological parameters (Navarro, Frenk & White 1997)

The ‘NFW’ profile

\[
\frac{\rho(r)}{\rho_{\text{crit}}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}
\]
The abundance of Milky Way satellites

Cumulative Number

Circular Velocity

Moore et al. 1999

Simulated cluster
Simulated galaxy
Virgo cluster data

dSph’s
Fornax
Sagittarius
SMC
LMC
The (corrected) abundance of Milky Way satellites

From Simon White
The angular momentum of observed and simulated disks

Angular momentum is transferred from the baryons to the dark matter during mergers.

It is not easy to form disks that resemble observed spirals in CDM models!
Mergers and Disk Angular Momentum

Most of the angular momentum is in the orbit of the merging system.

Final disk angular momentum is much lower than that of the halo.

Steinmetz & Navarro 1997
Angular Momentum Transfer
During Mergers
Cold Dark Matter and Substructure

- Simulations show that a significant fraction of low mass halos accreted within larger structures are not fully destroyed but remain as ‘sub-halos’ or ‘substructure’ within the larger system.
- At face value, this presents two problems:
  - Dark satellites are far more numerous than known satellites of the Milky Way.
  - Milky Way disk heating by tidal encounters with substructure halos.
CDM halos on different scales

OBSERVED STRUCTURES

Coma
$10^{15}$ Mo

NGC 2997
$10^{14}$ Mo

Leo I
$10^{13}$ Mo

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DARK HALOS

Moore 2000
Dwarf Spheroidal Halos

\[
\begin{array}{|c|c|}
\hline
\text{Sculptor} & 6.6 & 150 \\
\text{Carina} & 6.8 & 290 \\
\text{Sextans} & 6.6 & 470 \\
\text{Leo II} & 6.7 & 225 \\
\hline
\end{array}
\]

\[
\sigma^2 = \frac{1}{3} \frac{1}{M_*} \int V_c^2(r) \frac{dM}{dr} dr \approx \frac{1}{3} V_c^2(r_h)
\]

\[
\sigma = \frac{1}{\sqrt{3}} f \left( \frac{r}{r_{\text{max}}} \right) V_{\text{max}}
\]

For ΛCDM simulations \( T_{\text{max}} \approx 5 \text{ kpc} \frac{V_{\text{max}}}{20 \text{ km/s}} \)

For NFW shape: \( \sigma = 6.5 \quad r_h = 300 \Rightarrow V_{\text{max}} = 22 \text{ km/s} \)

Dark Halos are shallower than isothermal (logarithmic slope >-2) near the center.

S.D.M. White 2000
Potential Problems for CDM (IV):

• Cold Dark Matter halos are dense: about $10^{11} \, M_{\text{sun}}$ of dark matter are expected within $\sim 8$ kpc for the Milky Way. (At odds with observational estimates in our Milky Way?)
From COBE to BOOMERANG

The seeds of structure formation
The Matter-Energy Density of the Universe: brought to you by BOOMERANG

\[ \Omega > 1 \quad \Omega = 1 \quad \Omega < 1 \]
BOOMERANG vs SUPERNOVAE

Cosmological Constant = Vacuum Energy

\( \Omega_\Lambda \)

\( \Omega_m \)

Matter Density

No Big Bang

Expanding Forever

Recollapsing Eventually

closed

flat

open