The Mass Discrepancy Problem: New Physics in Matter or Gravity?

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What gets us into trouble is not what we don’t know.

It’s what we know for sure that just aint so.

- Mark Twain
A few things we know for sure...

$$\nabla^2 \Phi = 4\pi G \rho$$
$$F = ma$$

which basically means

$$mV^2/R = GMm/R^2$$

i.e,

$$V^2 = GM/R$$

ergo...

The universe is filled with nonbaryonic cold dark matter.
Spiral Galaxy Rotation Curve

Longer arrows represent larger orbital velocities.
Axioms

WIMPs

Neutron Stars

White Dwarfs

Strange Matter

First Stars

Brown Dwarfs

Jupiters

Asymmetric gravity

Cold DM

Hot DM

Non-Baryonic

Baryonic

MACHOs

Dark clusters

Cold Gas

??

Mass

Dynamics

Inertia

MOND

Weyl gravity

MOND

Ω = 1

Large Scale Structure

Bulk flows

Disk DM

Oort

discrepancy

Spiral galaxy

flat rotation curves

Cluster Velocity

dispersions

M_L / M_t \leq 300

M_X / M_t \leq 0.2

M_{_5} / M_{_r} \times 0.1

M_{_r} / M_{_m} \times 0.2
Galaxy Cluster
Axions  WIMPs  Neutron Stars  White Dwarfs  First Stars  Brown Dwarfs  Jupiters  Asymmetric gravity

Black Holes  Strange quarks

Cold DM  Non-Baryonic

MOND

Clustering  Dark Clusters

Cold Gas  MACHOs

\(\Omega = 1\)

Dynamics  Gravity  Inertia

\(M_\sigma / M_r \times 0.1\)

\(M_x / M_r \times 0.2\)

Large Scale Structure  Bulk flows

Neighboring galaxy flat rotation curves

Disk DM  Oort discrepancy

\(M_{\text{L}} / M_r \geq 300\)
Large Scale Structure
Pruning the tree

Baryonic Dark Matter

Many candidates:
  brown dwarfs
  Jupiters
  very faint stars
  very cold molecular gas
  warm ($\sim 10^5$ K) ionized gas

Can usually figure out a way to detect them: most have been ruled out.
Pruning the tree

Hot Dark Matter

Obvious candidate:
neutrinos

neutrinos got mass!...
...but not enough.

Also
- neutrinos suppress structure formation
- can’t crowd together closely enough
Pruning the tree

Cold Dark Matter

Some new particle, usually assumed to be **WIMPs** (Weakly Interacting Massive Particle)

don’t interact electromagnetically, so very dark.

Two big motivations:

1) total mass outweighs normal mass from BBN
   \[ \Omega_m \approx 6 \Omega_b \]
2) needed to grow cosmic structure
There isn’t enough time to form the observed cosmic structures from the smooth initial conditions unless there is a component of mass independent of photons. 

\[ t = 1.8 \times 10^5 \text{ yr} \]

very smooth: \( \frac{\delta \rho}{\rho} \sim 10^{-5} \)

\[ t = 1.4 \times 10^{10} \text{ yr} \]

very lumpy: \( \frac{\delta \rho}{\rho} \sim 1 \)

\[ \frac{\delta \rho}{\rho} \propto t^{2/3} \]

Both (1) and (2) hold only when gravity is normal.
“Cosmologists are often wrong, but never in doubt”
- Lev Landau

Things we know for sure in cosmology:

pre-1990:
\[ \Omega_m = 1.00 \]
\[ \Omega_\Lambda = 0.00 \]
\[ \Omega_b h^2 = 0.0125 \]
\[ H_0 = 50 \text{ km/s/Mpc} \]

Dark Matter = Cold Dark Matter
“Cosmologists are often wrong, but never in doubt”
- Lev Landau

Things we know **for sure** in cosmology:

2006:

\[
\begin{align*}
\Omega_m &= 0.24 \\
\Omega_\Lambda &= 0.76 \\
\Omega_b h^2 &= 0.0223 \\
H_0 &= 73 \text{ km/s/Mpc}
\end{align*}
\]

Dark Matter = **Cold Dark Matter**

What did I say?
On Galaxy Scales...

- Measure rotation velocity; find
- Properties depend systematically on
  - Total Baryonic Mass
  - Baryon Distribution
  - Acceleration
High Surface Brightness (HSB)

Low Surface Brightness (LSB)

Azimuthally averaged light distribution typically exponential for spiral disks.
NGC 2403

Stars

HI gas

\[ V \sin i = V_{\text{sys}} + V_c \cos \theta + V_r \sin \theta \]
NGC 6946

Stars

H I gas

Boomsma 2005
NGC 6946: $\mathcal{M}_*/L_B = 1.1 \mathcal{M}_\odot/L_\odot$
$M_\ast = (M/L)_\ast L$

Tully-Fisher Relation
Baryonic Tully-Fisher Relation

\[ M_d = M_* + M_g \]

\[ \log_{10} M_d (M_\odot) \]

\[ \log_{10} V_{flat} \]
CDM TF Relation

$M \sim V^3$

$\mu = 0.17$

$M = 50 V^4$

Slope and normalization wrong
Small scatter poses a fine-tuning problem

\[ m_d = \frac{M_{\text{disk}}}{M_{\text{tot}}} \]

\[ (m_d \leq f_b) \]
Newton says \[ V^2 = \frac{GM}{R}. \]
Equivalently, \[ \Sigma = \frac{M}{R^2} \]
\[ V^4 = G^2 M \Sigma \]

Therefore different \( \Sigma \) should mean different TF normalization.

\[ \mu = -2.5 \log \Sigma + C \]

\( \mu_o < 21.2 \)
\( 21.2 < \mu_o < 22.2 \)
\( 22.2 < \mu_o < 23.2 \)
\( \mu_o > 23.2 \)
NGC 2403

UGC 128

Same global L,V

Very different mass distributions
$R_p \approx 2.2h$
No Residuals from TF rel’n

Not even where disk contribution is maximal
Requires fine balance between dark & baryonic mass

\[ \frac{V_{\phi}}{V_p} : \frac{V_{K^*}}{V_p} \]

\[ \Sigma_{K^*} \text{ (}\mu\text{M}_\odot \text{pc}^{-2}) \]

\[ \Sigma_b \text{ (}\mu\text{M}_\odot \text{pc}^{-2}) \]

\text{Phys. Rev. Lett. 95, 171302 (2005)}
Dynamics knows about the distribution of light as well as the total mass.

Radius measured by disk scale length $h$

- **NGC 2403**
  - $M_B = -19.2$
  - $V_f = 134$ km s$^{-1}$
  - $\mu_0^f = 21.4$ mag/[]
  - $h = 2$ kpc

- **UGC 128**
  - $M_B = -18.8$
  - $V_f = 130$ km s$^{-1}$
  - $\mu_0^f = 24.2$ mag/[]
  - $h = 7$ kpc
Renzo’s Rule:

“When you see a feature in the light, you see a corresponding feature in the rotation curve.”

(Sancisi 1995, private communication)

The distribution of mass is coupled to the distribution of light.

Quantify by defining the Mass Discrepancy:

\[
D = \frac{V^2}{V_b^2} = \frac{V^2}{\Upsilon_* v_*^2 + V_g^2}
\]
74 galaxies
> 1000 points
(all data)

60 galaxies
> 600 points
(errors < 5%)
Different choices of Stellar Mass-to-Light Ratio

All data

$\sigma_V/V < 5\%$

Mass Discrepancy

$g_N (\text{km}^2 \text{s}^{-2} \text{kpc}^{-1})$

$g_N (\text{km}^2 \text{s}^{-2} \text{kpc}^{-1})$
Unexplained Correlations

- Tully-Fisher relation
- Mass discrepancy-acceleration relation
- dark matter/baryon see-saw
MOND
MODified Newtonian Dynamics
introduced by Moti Milgrom in 1983

Instead of dark matter, suppose the force law changes such that

\[
\begin{align*}
\text{for } a >> a_0, & \quad a \Rightarrow g_N \\
\text{for } a << a_0, & \quad a \Rightarrow \sqrt{g_N a_0}
\end{align*}
\]

where

\[g_N = \frac{GM}{R^2}\]

is the usual Newtonian acceleration.

More generally, these limits are connected by a smooth interpolation fcn \(\mu (a/a_0)\) so that

\[\mu (a/a_0) a = g_N.\]

MOND can be interpreted as a modification of either inertia (\(F = ma\)) or gravity (the Poisson eqn).
MOND predictions

- The Tully-Fisher Relation
- Slope = 4
- Normalization = 1/(aG)

Fundamentally a relation between Disk Mass and $V_{\text{flat}}$
- No Dependence on Surface Brightness

- Dependence of conventional M/L on radius and surface brightness
- Rotation Curve Shapes
- Detailed Rotation Curve Fits
- Surface Density $\sim$ Surface Brightness
- Stellar Population Mass-to-Light Ratios

"Disk Galaxies with low surface brightness provide particularly strong tests"

None of the following data existed in 1983. At that time, LSB galaxies which were widely thought not to exist.
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In MOND limit of low acceleration

\[ a = \sqrt{g_N a_0} \]

\[ \frac{V^2}{R} = \sqrt{\frac{GM}{R^2}} a_0 \]

\[ V^4 = a_0 GM \]

observed TF!
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\[ \xi = \frac{v^2}{(Gh)} \]

NGC 3726

NGC 3726

NGC 3769 *

NGC 3769 *

NGC 3877

NGC 3877

NGC 3883 *

NGC 3883 *

NGC 3917

NGC 3917

NGC 3949

NGC 3949

NGC 3953

NGC 3953

NGC 3972

NGC 3972

NGC 3992

NGC 3992

NGC 4010

NGC 4010

NGC 4013

NGC 4013

NGC 4051 *

NGC 4051 *

NGC 4085

NGC 4085

NGC 4088 *

NGC 4088 *

NGC 4100

NGC 4100
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Line: stellar population model
(mean expectation)
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<td>CMB Cosmography</td>
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</table>
MOND works. Either

MOND is correct, or

Dark Matter mimics MOND

Either way, new physics is implicated:

- gravity?
  \[ a_0 \sim cH_0 \sim c\Lambda^{1/2} \]

- new properties of dark matter?

"I think you should be more explicit here in step two."
No CDM prediction (McGaugh 1999): \( A_{1:2} = 2.4 \)

\[
A_{1:2} = 2.34 \pm 0.09
\]
No CDM fit to WMAP data
BBN: \[ \omega_b = \Omega_b h^2 \propto \eta_{10} \]
$\langle A_{\text{Li}} \rangle = 2.37 \text{ dex (}\sigma = 0.06 \text{ dex)}$

$T_{\text{eff}} > 6000 \text{ K}$
AND YOUR SCIENTIFIC CONCLUSIONS?

CDM IS A FIB.

THE STATE RESTS.

THE EARTH ISN'T ROUND, EITHER.

SAVE IT!

YEP! IT'S SHAPED LIKE A BURRITO!