Empirical Tests of MOND in Galaxies

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Cosmological Constraints

age = 13 Gyr

SNIa and CMB want similar numbers, so it must be true!
FLRW cosmology only works with:
- dark matter
- dark energy

We don’t know what dark matter is and we don’t understand what dark energy means.
Does dark matter exist?

But we behave like we’re pretty darn sure that dark matter is made of WIMPs.
Interpretation in terms of dark matter leads to fine-tuning problems.
Global Relation: Stars only

\[ M_\ast = \Gamma L \]

Tully-Fisher Relation

- Red squares: Pizagno et al.
Global Relation:

Stars plus gas

\[ M_b = M_\star + M_{\text{gas}} \]

Baryonic Tully-Fisher line:

\[ \log M_b = 4 \log V_f + 1.7 \]

(McGaugh 2005)

Implies no other substantial reservoirs of baryonic mass.
NGC 2403

UGC 128

Same global $M_b, V$

Very different mass distributions

de Blok & McGaugh (1996)
Tully & Verheijen (1997)
Newton says\[ V^2 = GM/R. \]
Equivalently, \[ \Sigma = M/R^2 \]
\[ V^4 = G^2M\Sigma \]

Therefore different \( \Sigma \) should mean different TF normalization.
No Residuals from TF rel’n

Sometimes interpreted to mean that dark matter dominates over disk mass
Acceleration related to baryonic surface density

Baryons important to dynamics - dark matter does not dominate.
A contradiction to purely Newtonian dynamics?

\[ \frac{V_p^2}{R_p} \text{ (km}^2 \text{s}^{-2} \text{kpc}^{-1}) \]

\[ \Sigma_b \text{ (M}_\odot \text{ p c}^{-2}) \]

central baryonic surface density
Fine-tuning unavoidable


“...working on the thing can drive you mad.”
MOND

\[ a \gg a_0 \quad \text{a} \rightarrow g_N \]

\[ a \ll a_0 \quad a \rightarrow \sqrt{g_N a_0} \]

\[ a_0 \approx 1 \text{Å s}^{-2} \]

\[ \mu \left( \frac{a}{a_0} \right) = \frac{g_N}{a} \]

\[ \mu \rightarrow 1 \quad a \gg a_0 \]

\[ \mu \rightarrow \frac{a}{a_0} \quad a \ll a_0 \]
MODIFICATION OF NEWTONIAN DYNAMICS

The main predictions concern the following.

1. Velocity curves calculated with the modified dynamics on the basis of the observed mass in galaxies should agree with the observed curves. Elliptical and 50 galaxies may be the best for this purpose since (a) practically no uncertainty due to obscuration is involved and (b) there is not much uncertainty due to the possible presence of molecular hydrogen.

2. The relation between the asymptotic 

\[ V_R \] 

and the mass of the galaxy (\( M \)) \( \propto \) \( (V_R^2) \) is an absolute one.

3. Analysis of the z-dynamics in disk galaxies using the modified dynamics should yield surface densities which agree with the observed ones. Accordingly, the same analysis using the conventional dynamics should yield a discrepancy which increases with radius in a predictable manner.

4. Effects of the modified dynamics are predicted to be particularly strong in dwarf elliptical galaxies (for review of properties see, e.g., Hodge 1971 and Zinn 1980). For example, those dwarfs believed to be bound to our Galaxy would have internal accelerations typically of order \( a_{in} \approx a_{o/30} \). Their (modified) acceleration, \( a_{in} \), in the field of the Galaxy is larger than the internal one but still much smaller than \( a_{o/3} \), \( a_{in} \approx (8 \text{ kpc}/d) a_{o/3} \) based on a value of \( V_R = 220 \text{ km s}^{-1} \) for the Galaxy, and \( d \) is the distance from the dwarf galaxy to the center of the Milky Way (\( d \approx 70-220 \text{ kpc} \)). Whichever way the external acceleration turns out to affect the internal dynamics (see the discussion at the end of § II, the section on small groups in Paper III, and Paper I), we predict that when velocity dispersion data is available for the dwarfs, a large mass discrepancy will result when the conventional dynamics is used to determine the masses. The dynamically determined mass is predicted to be larger by a factor of order 10 or more than that which can be accounted for by stars. In case the internal dynamics is determined by the external acceleration, we predict this factor to increase with \( d \) and be of order \( (d/8 \text{ kpc}) \) (as long as \( a_{in} \approx a_{in/30} \), \( a_{in/30} = 1 \)).

Prediction 1. is a very general one. It is worthwhile listing some of its consequences as separate predictions, numbered 5-7 below (note that, in fact, even prediction 1 is already contained in prediction 1).

5. Measuring local M/L values in disk galaxies (assuming conventional dynamics) should give the following results: In regions of the galaxy where \( V_R^2/\rho \gg a_{o/30} \) the local M/L values should show no indication of hidden mass. At a certain transition radius, local M/L should start to increase rapidly. The transition radius is given by \( a_{o/30} = \left( \frac{1}{2} \right) \frac{V_R^2}{\rho} \). As the transition radius is crossed, we expect a steep increase in M/L as we are concerned only with variations of this quantity; (b) Effects of the modified dynamics manifest themselves more drastically if a galaxy is observed at a larger distance where the concentration of local behavior in the disk only while the spherical can be neglected. This makes the determination of mass from velocity more certain.

6. Disk galaxies with low surface brightness provide particularly strong tests. A study of a sample of such galaxies is described by Strom 1982 and by Romanishin et al. 1982. As low surface brightness means small accelerations, the effects of the modification should be more noticeable in such galaxies. We predict, for example, that the proportionality factor in the \( M \propto V_R^2 \) relation for these galaxies is the same as for normal surface density galaxies. In contrast, if one wants to obtain a correlation \( M \propto \rho^{-1/2} \) in the conventional dynamics (with additional assumptions), one is led to the relation \( M \propto \rho^{-1/2} \) (see, for example, Aaronson, Huchra, and Mould 1979), where \( \rho \) is the average surface brightness. This implies that low surface density galaxies of a given velocity, have a mass higher than predicted by the \( M \propto V_R^2 \) relation derived for normal surface density galaxies.

We also predict that the lower the average surface density of a galaxy is, the smaller is the transition radius, defined in prediction 3, in units of the galaxy's scale length. In fact, if the average surface density is very small we may have a galaxy in which \( V_R^2/\rho < a_{o/30} \) everywhere, and analysis with conventional dynamics should yield low M/L values starting to increase from very small radii.

IX. DISCUSSION

The main results of this paper can be summarized by the statement that the modified dynamics eliminates the need to assume hidden mass in galaxies. The effects in galaxies which I have considered, and which are commonly attributed to such hidden mass, are readily explained by the modification. More specifically:

- The Tully-Fisher Relation
- Normalization = 1/(\( a_{o/30} \))
- Fundamentally a relation between Disk Mass and \( V_{flat} \)
- No Dependence on Surface Brightness
- Dependence of conventional M/L on radius and surface brightness
- Rotation Curve Shapes
- Surface Density ~ Surface Brightness
- Detailed Rotation Curve Fits
- Stellar Population Mass-to-Light Ratios
The Tully-Fisher Relation

- Slope = 4
- Normalization = $1/(a_0 G)$
- 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
- Surface Density ~ Surface Brightness
- Detailed Rotation Curve Fits
- Stellar Population Mass-to-Light Ratios
Rotation curves of spirals and low mass dIrrs with $M^* < M_g$. 

Rotation curves of late type disks (Sd, Sm, Irr) 

Kuzio de Naray et al. (2006, 2008, 2009); Trachternach et al. (2009)
M* > M_g (H-band popsynth)
Sakai (2000); Gurovich et al. (2010)

M* > M_g (MOND fits)
McGaugh (2005)

M* < M_g (V_c = W_20/2)
Gurovich et al. (2010)

M* < M_g \sin(i_{opt}) < 1.12 \sin(i_{HI})
Begum et al. (2008)

M* < M_g
Stark et al. (2009)

M* < M_g
Trachternach et al. (2008)

Position on BTFR independent of stellar M*/L for M* < M_g
• MOND accurately predicts the BTF location of gas dominated galaxies with zero free parameters.

• CDM does not do this.
The Tully-Fisher Relation

Slope = 4
Normalization = $1/(a_0 G)$

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

Surface Density $\sim$ Surface Brightness

Detailed Rotation Curve Fits

Stellar Population Mass-to-Light Ratios

MOND predictions

- The Tully-Fisher Relation
- Slope = 4
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- Surface Density $\sim$ Surface Brightness
- Detailed Rotation Curve Fits
- Stellar Population Mass-to-Light Ratios

$23.2 < \mu_0$
$22.2 < \mu_0 < 23.2$
$21.2 < \mu_0 < 22.2$
$\mu_0 < 21.2$
The Tully-Fisher Relation

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Rotation Curve Shapes

- Surface Density ~ Surface Brightness
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predictive power: zero free parameters

NGC 4157

$V$ (km s$^{-1}$) vs. $R$ (kpc)

$K'$-band stellar population prediction

MOND fit
NGC 6946 - small bulge predicted

Renzo’s Rule:
“When you see a feature in the light, you see a corresponding feature in the rotation curve.”
NGC 6946 - small bulge observed

Renzo's Rule:
“When you see a feature in the light, you see a corresponding feature in the rotation curve.”
Residuals of MOND fits

$\Delta V/V$

$R$ (kpc)

All data

$\sigma_{V/V} < 5\%$
The Tully-Fisher Relation
- Slope = 4
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MOND predictions
- The Tully-Fisher Relation
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- Stellar Population Mass-to-Light Ratios
Line: stellar population model (mean expectation)
The Tully-Fisher Relation

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MOND predictions

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Can we reverse the procedure?

Rather than fitting rotation curves given the photometry, can we infer the baryonic mass distribution from the rotation curve?

Milky Way terminal velocities
initial guess
final fit
Obtain plausible mass profile; predictions testable with GAIA

McGaugh (2008)
Allowing for a significant bulge component implies that the Milky Way has a Type II disk.
Other tests - e.g., disk stability (Milgrom 1989)

\[ G \Sigma_\ast = a_0 \]
Figure 11: The growth rate, in units of the dynamical time, for the m=2 mode as a function of the total mass of the disk. □ MOND, △ Newtonian + Halo.
LSB galaxies got spiral arms!

To explain this, we anticipate the need for very massive disks to drive spiral density waves in LSBs

## Disk Masses from Density Waves

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<tr>
<th>Galaxy</th>
<th>(M/L)*</th>
<th>AUTHOR</th>
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</tr>
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Conventional analysis overestimates M*/L, as expected
Other tests - other systems

\[ \log(\sigma_1) \text{ (} \text{km/s} \text{)} \]

\[ \log(r) \text{ (} \text{pc} \text{)} \]

- Ellipticals
- Clusters
- Globular Clusters
- Giant Molecular Clouds
- Dwarf Spheroidals

(from Sanders)
Assumes

\[ \Upsilon_\star = 1 \]

\[ V_c = \sqrt{2}\sigma \]
No scale length residuals for Galaxies...

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

...but there are for Globular Clusters

Newton works (as he should in high density systems)
Dwarf Spheroidals

MOND $M^*/L$ OK for most classical dwarfs but unacceptably high for ultrafaints.
Residuals of dwarf Spheroidals from Baryonic Tully-Fisher Relation
McGaugh & Wolf (2010)

Local dwarf data: Wolf et al. (2010)  
Kalirai et al. (2009; M31)  
M*/L as per Mateo et al. (1998)  
& Martin et al. (2008)

\[ F_b = \frac{M_b}{AV_c^4} \]
dSph BTFR residuals correlate with

\[ F_{T,D} = \frac{M}{m} \left( \frac{r}{D} \right)^3 \]
tidal radii in dark matter and MOND

\[ r_t = r_{t, \text{phot}} \]
Dwarfs whose stars have little time to adjust to changes in the potential suffer the largest deviations and have more elliptical shapes.

That the ultrafaints are tidally affected by the Milky Way in MOND. Their M*/L are overestimated by the usual equilibrium calculation.
Clusters have less baryonic mass than expected.

Cluster data: Giodini et al. (2009)

\[ M_\Delta = B_\Delta V_\Delta^3 \]

\[ B_{500} = 1.5 \times 10^5 \, M_\odot \, \text{km}^{-3} \, \text{s}^{-3} \]

Spiral data: McGaugh et al. (2005)

Gas dominated disks:
Stark et al. (2009)
Trachternach et al. (2009)

Local dwarf data: Walker et al. (2009)
M*/L as per Mateo et al. (1998)

\[ V_c = \sqrt{3} \sigma \]

Why do Clusters deviate?

Clusters have less baryonic mass than expected.

Deviations might plausibly be explained by tides in MOND

McGaugh et al. (2010)
residual mass discrepancy in clusters is real...
the bullet cluster is a special case of a more general problem.
1E 0657-56 - “bullet” cluster (Clowe et al. 2006)
observed shock velocity

CDM bullet cluster collision velocity

mass discrepancy more naturally explained by CDM

Tidal Debris Dwarfs - should be devoid of Dark Matter

Bournaud et al. (2007) *Science*, 316, 1166
Gentile et al. (2007)
*A&A, 472, L25*

Tidal dwarfs do show mass discrepancies as expected in MOND
Conclusions

• MOND naturally explains a diverse array of phenomena

• Many \textit{a priori} MOND predictions have been realized; some problems remain, especially in rich galaxy clusters

• The observed MONDian phenomenology is not naturally a part of the $\Lambda$CDM paradigm

• Can CDM be falsified???
No CDM prediction (McGaugh 1999): $A_{1:2} = 2.4$

Subsequent measurement: $A_{1:2} = 2.34 \pm 0.09$