Astronomical and Experimental Tests of MOND

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\( \Lambda \text{CDM} \)

the modern standard “concordance” cosmological model

- Baryons
- Dark Matter 23%
- Dark Energy 73%
- Einstein’s \( \Lambda \) and modern generalizations
- non-baryonic cold dark matter (e.g., WIMPs)
“Traditional” observational cosmology: directly measure the Hubble constant, mean mass density, and age of globular clusters.
Indeed, in the familiar case of adding a cosmological constant, it is largely a matter of taste whether to call it modified gravity or dark energy, corresponding merely to whether we insert it on the left or right hand side of the Einstein equations." (Tegmark 2002, PRD, 66, 3507)
Lots of evidence for dark matter - or more properly, mass discrepancies
Flat rotation curves of spiral galaxies

NGC 6946

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Newton says
\[ V^2 = GM/R. \]

Equivalently,
\[ \Sigma = M/R^2 \]
\[ V^4 = G^2 M \Sigma \]

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

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

\[ \mu_o < 21.2 \]
\[ 21.2 < \mu_o < 22.2 \]
\[ 22.2 < \mu_o < 23.2 \]
\[ \mu_o > 23.2 \]
The mass discrepancy does not appear at a particular length scale.

The mass discrepancy does appear at a particular acceleration scale.

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60 galaxies

$> 600$ points

(errors $< 5\%$)
MOND
Modified Newtonian Dynamics
introduced by Moti Milgrom in 1983

Above a critical acceleration $a_0$ everything is normal. Below that scale, gravity in effect becomes stronger.

Newtonian $a = g_N$ for $a \gg a_0$

MOND $a = \sqrt{g_N a_0}$ for $a \ll a_0$

$a_0 \approx 10^{-10} \text{ m s}^{-2}$

Paste regimes together with smooth interpolation function

$$\mu \left( \frac{a}{a_0} \right)$$
Two possible interpretations

Modify Inertia:

\[ a = \frac{F}{m} \rightarrow \frac{F}{m\mu(a/a_0)} \]

Modify Gravity:

\[ \nabla^2 \Phi \rightarrow \nabla \left[ \mu \left( \frac{|\nabla \Phi|}{a_0} \right) \nabla \Phi \right] = 4\pi G \rho \]

Of course, need a generally covariant parent theory (e.g., TeVeS)
The Tully-Fisher Relation
- Slope = 4
- Normalization = 1/(a_0G)
- Fundamentally a relation between Disk Mass and V_{flat}
- No Dependence on Surface Brightness

MOND predictions
- 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

Disk Galaxies with low surface brightness provide particularly strong tests
• The Tully-Fisher Relation
  • Slope = 4
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  • No Dependence on Surface Brightness

MOND predictions

• 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
In MOND regime

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

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

\[ V^4 = a_0 GM \]

Observed Tully-Fisher Relation.
No dependence on radius/surface density
Green line is MOND prediction
MOND accurately predicts the location of low mass, gas rich galaxies with no free parameters.
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\[ \xi = \frac{V^2}{(Gh)} \]

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Gets the bumps & wiggles in light distribution & rotation curve
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Line: stellar population model
(mean expectation)
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**MOND predictions**

**MOND is the effective force law in spiral galaxies**
Other MOND tests

Astronomical

- Disk Stability
- Freeman limit in surface brightness distribution
- thin disks
- velocity dispersions
- LSB disks not over-stabilized
  \[ \sigma \approx 10 \text{ km s}^{-1} \text{ at } \Sigma \approx 1 \text{ M}_\odot \text{ pc}^{-2} \]
- Dwarf Spheroidals
- Giant Ellipticals
- Clusters of Galaxies (cured if neutrino mass \( \sim 1 \text{ eV} \))
- Structure Formation
  - Microwave background
  - 1st:2nd peak amplitude; BBN
    \[ \Omega_b h^2 \approx 0.017 \]
  - early reionization
  - enhanced ISW effect
  - 3rd peak

Experimental

- Send satellite far from sun
  - Pioneer anomaly
  - need to get \( \sim 0.1 \) light-year away from the sun to be sure

- Send satellite to where potential vanishes between Earth & Sun
  (Magueijo & Bekenstein 2007)
  - Need \( |\nabla \Phi| < a_0 \)
  - All planets matter to location

- Inertial jump at high longitude when all vectors cancel
  (Ignatiev 2008)
Take home conclusions

• The mass discrepancy appears at a particular acceleration scale

\[ a_0 \approx 1 \text{ Å/s/s} \]

• length-scale based modifications are excluded

• This acceleration scale appears to be a cosmic one

\[ a_0 \sim cH_0 \sim c\sqrt{\Lambda} \]

• A modification of gravity (or inertia!) is a viable solution to the dark matter problem. Can we simultaneously solve dark energy?