THINGS about MOND

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Benoit Famaey, Erwin de Blok
Introduction: what are rotation curves?

Rotation velocity of gas and/or stars as a function of radius $V_{\text{rot}}(r)$: traced via different lines: Hα, HI, CO, …

Pizzella et al. (2004)
Introduction: rotation curves from HI data

Rotating disk:

Data cube (series of maps @ slightly different freq.) should look like this:

<table>
<thead>
<tr>
<th>2639.7</th>
<th>2681.0</th>
<th>2722.2</th>
<th>2763.4</th>
<th>2804.6</th>
</tr>
</thead>
<tbody>
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</table>

receding velocity (km/s)
Introduction: rotation curves from HI data

Rotating disk:

Data cube (series of maps @ slightly different freq.) should look like this:

What about real observations?
Why are rotation curves interesting?

Rotation curves do not decline as expected from the visible matter.

1) Dark matter halo

or

2) gravity is "boosted" below a certain acceleration \( a_0 \sim 10^{-8} \text{ cm s}^{-2} \)

Modified Newtonian Dynamics (MOND) – Milgrom (1983)

NGC 3198: adapted from Begeman et al. (1991)
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MOND in disk galaxies: Universal Rotation Curve from MOND?

Universal Rotation Curve: parametrization such that: Vel.(radius,luminosity)

Gentile (2008)

Black: original URC
Red: “URC” from MOND
The THINGS survey

- THINGS = The HI Nearby Galaxy Survey
- 34 nearby galaxies (2 Mpc < Distance < 15 Mpc)
- HI emission – high spectral and spatial resolution
- galaxies chosen to span wide range of properties
The THINGS survey
The THINGS survey

• de Blok et al. (2008) analyse 17 rotation curves selection based on inclination angle, regular kinematics etc.

• mass decomposition: Newtonian gravity, baryons, dark matter
The cusp/core discrepancy

- Cold Dark Matter works well on large scales (Cosmic Microwave Background, large scale structure,...)
- But problems on galaxy scales!

- cusp/core problem:

Best understood effect of baryons: adiabatic contraction
It would make CDM halos even more concentrated…

Gentile et al. (2005)
MOND in tidal dwarf galaxies: Rotation curves


Gentile et al. (2007)

Black curve: MOND (*not* at fit, zero free parameters!!)

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THINGS about MOND

• From de Blok et al. (2008) we eliminate a few more galaxies because of non-circular motions

“The highest quality HI rotation curves available to date for a large sample of nearby galaxies” (de Blok et al. 2008)

→ 12 rotation curves to be analysed in MOND

Rotation curves: 40 - 290 independent points per galaxy

For 7/12 galaxies, precise estimate of distance (Cepheids, TRGB)
MOND interpolation functions

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

\( g \): MOND gravitational acceleration

\( g_N \): Newtonian gravitational acceleration

\[ \mu(x) \approx x \text{ for } x << 1 \]

\[ \mu(x) \approx 1 \text{ for } x >> 1 \]

“Standard” interpolation function

\[ \mu(x) = \frac{x}{\sqrt{1 + x^2}} \]

Milgrom (1983)

“Simple” interpolation function

\[ \mu(x) = \frac{x}{1 + x} \]

Famaey & Binney (2005)
We make MOND fits with the two interpolation functions

First, we fix the distances and leave $a_0$ as a free parameter (stellar M/L ratio is the other free parameter)

The median values are very similar to previous studies:
$a_0 = 1.27 \times 10^{-8} \text{ cm s}^{-2}$ for the standard $\mu$ function
$a_0 = 1.22 \times 10^{-8} \text{ cm s}^{-2}$ for the simple $\mu$ function
MOND fits to THINGS rotation curves

- We make MOND fits with the two interpolation functions

- First, we fix the distances and leave $a_0$ as a free parameter (stellar M/L ratio is the other free parameter)

We do not confirm the correlation between central surface brightness & best-fit $a_0$ (Swaters+10, 1005.5456)
MOND fits to THINGS rotation curves

• We make MOND fits with simple and standard interpolation functions

• We consider 3 possibilities for the distance
  1) fixed
  2) constrained
  3) free

• stellar M/L ratio: free parameter
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NGC 2976

MOND

Newton+
dark matter
MOND fits to THINGS rotation curves
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NGC 3198

MOND

Newton+
dark matter
MOND fits to THINGS rotation curves

NGC 3198
This is with the distance constrained
Cepheids: 13.8 ± 1.5 Mpc

What if we leave the distance completely free?
MOND fits to THINGS rotation curves

NGC 3198
This is with the distance constrained
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What if we leave the distance completely free?

Price to pay: distance of 8.6 Mpc
MOND fits to THINGS rotation curves

NGC 3198
This is with the
distance
constrained
Cepheids:
13.8 ± 1.5 Mpc

Resemblance between residuals (full circles) and non-circular motions (open circles)
Stellar M/L ratios

Solid line: Bell & de Jong (2001), scaled-down Salpeter IMF

We confirm previous results (e.g. Sanders & McGaugh 2002)
Mass discrepancy – acceleration relation

Log (gravitational acceleration of baryons – km\(^2\) s\(^{-2}\) kpc\(^{-1}\))

A constant “dark matter” acceleration?

Walker et al., 1004.5228, ApJL in press
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From the THINGS sample
A constant “dark matter” acceleration?

Walker et al., 1004.5228, ApJL in press

From the THINGS sample
Conclusions

- THINGS (The HI Nearby Galaxy Survey): high-quality rotation curves
- MOND analysis of 12 rotation curves from the THINGS sample
- 9/12 galaxies have excellent fits
- Among the 3 poorest fits, 2 galaxies also have poor Newton + DM fits
- NGC 3198 has some tension between MOND fit and observations
  Non-circular motions?
- We reproduce the mass discrepancy – acceleration relation
- Constant “dark matter” acceleration: maybe due to limited range in $g_N$