Dynamical friction, galaxy merging, and radial-orbit instability in MOND

Carlo Nipoti
Dipartimento di Astronomia
Università di Bologna

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Outline

- MOND and Equivalent Newtonian Systems
- Dynamical friction
- Galaxy merging
- Radial-orbit instability
• Consider MOND in the formulation of Bekenstein & Milgrom (1984)

• MOND field equation:

\[ \nabla \cdot \left[ \mu \left( \frac{\| \nabla \phi \|}{a_0} \right) \nabla \phi \right] = 4\pi G \rho_* \]
Equivalent Newtonian System (ENS)  
*(see Milgrom 2001; Nipoti et al. 2007)*

- Given a purely baryonic MOND system (e.g. galaxy) it is possible to build an ENS with dark matter halo

\[
\nabla^2 \phi = 4\pi G (\rho_\star + \rho_{DM})
\]

- MOND and ENS have the same total gravitational potential => same kinematics
MOND and ENS

High acceleration / baryon dominated

Low acceleration / DM dominated

Baryons: Hernquist sphere

Acceleration ratio:

\[ \kappa \equiv \frac{GM_*}{r_* a_0} \]
How can we distinguish MOND and ENS?

- Same kinematics (rotation curve or velocity dispersion profile)

- Differences in dynamical processes:
  - Dynamical friction
  - Galaxy merging
  - Radial-orbit instability
N-MODY: a code for N-body simulations in MOND

- We studied dynamical processes in MOND and ENS using N-body simulations
- N-MODY: Particle-Mesh N-body code with MOND potential solver

(Ciotti et al. 2006; Nipoti et al. 2007; Londrillo & Nipoti 2009)
Dynamical friction
Dynamical friction

(Nipoti, Ciotti, Binney & Londrillo 2008)

- Spherical N-body system (MOND and ENS)
- Small rigid bar rotating at the system's centre
- Measure slowing down of the bar due to DF
Dynamical friction

(Nipoti, Ciotti, Binney & Londrillo 2008)

Bar angular frequency

Time
Dynamical friction

(Ciotti & Binney 2004; Nipoti et al. 2008)

MOND/Newton
DF timescale

DM fraction (in ENS)
Dynamical friction: results

- DF is more effective in MOND than in ENS
- Valid in general for a massive object travelling in a swarm of lower mass particles
- Implication: MOND has problems explaining survival of globular clusters in Fornax dwarf sph \( (t_{\text{DF}} \sim 1\text{Gyr}) \)  
  
  (Sanchez-Salchedo et al. 2006; Nipoti et al. 2008)
Comment:
galactic bars and dynamical friction

- $M_{\text{bar}} \ll M_{\text{gal}} \Rightarrow$ bar slows down more in MOND than in ENS
- $M_{\text{bar}} \sim M_{\text{gal}} \Rightarrow$ bar does not slow down in MOND (no background particles!)

(see Tiret & Combes 2007; Nipoti et al. 2008)
Galaxy merging
Galaxy merging: MOND vs DM

(Nipoti, Londrillo & Ciotti 2007)

- Can galaxy merge in MOND?
- Lots of orbital kinetic energy to dissipate (as if there were DM), but no DM halos to absorb it!
- Check with N-body experiments
“Standard” galaxy encounter
*(Nipoti, Londrillo & Ciotti 2007)*

- Initial conditions:
- Two equal-mass, spherical galaxies at rest when at distance ≈ 100 R$_{\text{eff}}$
- Plus some orbital angular momentum
- Compare MOND (stars) and ENS (stars+DM)
“Standard” galaxy encounter
(Nipoti, Londrillo & Ciotti 2007)

NEWTONIAN GRAVITY

Baryons+Dark Matter (not shown)

MOND

Baryons only

$y/M_{10}^{1/2}$ kpc

$x/M_{10}^{1/2}$ kpc

$k=1$, $b_0=0.5$, $c_{esc}=200$. 

t = 0.00 $M_{10}^{1/4}$Gyrs
“Standard” galaxy encounter
(Nipoti, Londrillo & Ciotti 2007)

NEWTONIAN GRAVITY

MOND

Baryons+Dark Matter (not shown)

Baryons only

\[ t = 0.89 \, M_{10}^{1/4} \text{Gyrs} \]

\[ k = 1, \, b_0 = 0.5, \, d_{\text{sep}} = 200. \]
“Slow” galaxy encounter
(Nipoti, Londrillo & Cioffi 2007)

- Galaxies at rest when at distance $\approx 30 R_{\text{eff}}$
- Plus some orbital angular momentum
“Slow” galaxy encounter
(Nipoti, Londrillo & Ciotti 2007)

NEWTONIAN GRAVITY

Baryons+Dark Matter (not shown)

MOND

Baryons only
“Slow” galaxy encounter
(Nipoti, Londrillo & Ciotti 2007)

NEWTONIAN GRAVITY

Baryons+Dark Matter (not shown)

MOND

Baryons only

\[ t = 0.89 \frac{M_{10}}{\frac{1}{2}} \text{Gyrs} \]

\[ k = 1, b_0 = 0.5, d_{\text{sep}} = 60. \]
Galaxy merging: results

(Nipoti, Londrillo & Ciotti 2007)

- Very long merging timescales in MOND
- Evidence of rapid mergers hard to explain in MOND
Comment: merging & dynamical friction

- $t_{DF}^{\text{(MOND)}} < t_{DF}^{\text{(ENS)}}$
- $t_{\text{merg}}^{\text{(MOND)}} > t_{\text{merg}}^{\text{(ENS)}}$

- No contradiction
- When MOND galaxies interact DF is not at work because there is no DM halo to act as background
Radial-orbit instability
Dynamical instability

- MOND and ENS can be different in terms of dynamical stability
- It is not guaranteed that the MOND system is stable if the ENS is stable
- For example: galactic disks stabilized by DM halos (Ostriker & Peebles 1973)
- Stability of MOND disks (Milgrom 1989; Brada & Milgrom 1999)
Radial-orbit instability I

- Radially anisotropic pressure-supported systems can be subject to radial-orbit instability (ROI)
- We explore ROI in spherical galaxy models with Ossipkov-Merritt (OM) anisotropy
- Anisotropy radius $r_a$: smaller $r_a \Rightarrow$ more radial anisotropy

\[
\beta(r) = \frac{r^2}{r^2 + r_a^2}
\]

(Nipoti, Ciotti & Londrillo, in preparation)
Radial-orbit instability II

- (Nipoti, Ciotti & Londrillo, in preparation)

- Explore stability with N-body simulations
- We compare MOND, ENSs and purely baryonic Newtonian systems
- In ENS the DM halo is frozen (fixed potential)
Radial-orbit instability III

(Nipoti, Ciotti & Londrillo, in preparation)
Radial-orbit instability: results

- ROI more effective in MOND than in ENS
- Less radial anisotropy allowed in MOND
- Important when trying to reproduce in MOND kinematics of ellipticals, dwarf sphs and globular clusters
- Application: globular cluster NGC 2419 (see talk by A. Sollima this afternoon)

(Nipoti, Ciotti & Londrillo, in preparation)
Conclusions
Conclusions

- MOND and ENSs with DM can be distinguished studying dynamical processes
- Dynamical friction timescales shorter in MOND
- Galaxy merging timescales longer in MOND
- Radial-orbit instability more effective in MOND