Distribution of Baryonic Matter in Dark Matter Halos: Effect of Dynamical Friction

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Issues

• The distribution of dark matter particles: NFW Profile (or some variation, Jing & Suto 2000, Mamon & Lokas 2005)

• Distribution of ‘Light” (baryons): Hubble, de Vaucouleurs or Sersic profiles

• Why the central parts of the galaxies are so distinct?

• Origin of $M_{BH} - M_{\text{total}}$ relation?
Dark matter and baryons

- Dark matter: collisions
- Baryons: dissipation
  - Contraction
  - Expansion
- Response of dark matter depends on baryonic process
- Here we consider dynamical friction on baryonic matter conglomerates by dark matter particles

Dutton & Treu (2014)

\[ \gamma' = 3 - \frac{d \log M}{d \log r} \]
Assumptions

- Spherical systems
  - We do not consider disk galaxies
  - We do not consider rotation, but could be easily extended if the rotation is mild
- No velocity anisotropy
- Galaxies are composed of only two types of particles
  - Dark matter \((m_{\text{dm}}, M_{\text{dm}})\)
  - Baryons, but in the form of massive conglomerates \((m_b \gg M_{\text{sun}}, M_b < M_{\text{dm}})\)
- Initially, these two components follow the same density profile of NFW.
Dominant Dynamical Processes

- Equilibrium distribution of dark matter particles would remain almost static since the relaxation time scale is extremely large.

- Interaction between massive and less massive particles lead to dynamical friction.
  - Orbital decay and inspiral toward the central parts.
  - Redistribution of massive component

- Further collapse of the central core through gravothermal catastrophe
Time Scales

- Dynamical Friction ($m_{dm} << m_b$): Chandrasekhar’s formula

$$ t_{fric} = \frac{1.17 r_i^2 v_c}{\ln \Lambda \ G m_b} = 2.6 \times 10^9 \text{years} \left( \frac{10}{\ln \Lambda} \right) \left( \frac{r_i^2}{1 \text{kpc}} \right)^2 \left( \frac{v_c}{100 \text{km/s}} \right) \left( \frac{10^6 M_\odot}{m_b} \right) $$

(Binney & Tremaine 2008)

- Two-body Relaxation: could become important in the center.

$$ t_{relax} = \frac{v^3}{8\pi G^2 m^2 n \ln \Lambda} $$
Numerical Method

- Isotropic Fokker–Planck Equation for self-gravitating system

\[
4\pi^2 p(E) \frac{\partial f_i(E)}{\partial t} = - \frac{\partial}{\partial E} \left( -D_E f_i(E) - D_{EE} \frac{\partial f_i(E)}{\partial E} \right)
\]

\[
E = \frac{1}{2} v^2 + \phi(r)
\]

\[
\nabla^2 \phi(r) = 4\pi G \rho(r)
\]

- \( f_i(E) \): Phase space distribution function of the i-th component
- \( p(E), D_E, D_{EE} \): statistical weight, first and second-order Fokker–Planck coefficients
Initial Models

• Navarro–Frenk–White Density Distribution (Lokas 2001)

\[
\rho(r) = \frac{g(c)}{4\pi r (1 + r^2)} \frac{1}{r (1 + r^2)}
\]

\[
\phi(r) = -g(c) \frac{\ln(1 + r)}{r}
\]

\[
g(c) = \frac{1}{\ln(1 + c) - c/(1 + c)}
\]

c: concentration parameter (~10 for bright galaxies, Lockas & Mamon 2001)
Density-Distribution Function Pair

- Eddington’s Formula for isotropic distribution

\[
f(\varepsilon) = \frac{1}{\sqrt{8\pi^2}} \frac{d}{d\varepsilon} \int_0^{\Psi} \frac{d\Psi}{\sqrt{\varepsilon - \Psi}} \frac{d\rho}{d\Psi}
\]

- Both dark matter and baryonic conglomerates are assumed to follow the same density distribution initially
Test of Fokker–Planck against N-body

- F–P is known to work very well for initial models with flat core (i.e., King models, Plummer model, etc.)

- Since we applied F–P equation for cuspy initial models for the first time, we need to check against the N-body: good agreement with NBODY6

\[ \frac{m_2}{m_1} = 2. \]
Convergence Test

- The evolution depends on $\mu = m_b/m_{dm}$.
- One cannot have arbitrarily large value for $\mu$.
- The evolution, measured by $(t_{cc}/t_{fh} \rightarrow 7.1 \times 10^{-3})$ becomes independent of $\mu$ for large $\mu > 1000$. The distinct core develops in short time!

$M_B/M_{tot} = 0.1$
Evolution of the central density and velocity dispersion

solid: low mass (dark matter)
broken: (baryon)
dotted: total
Density Profiles

Virial radius

Half-mass radius

$t/t_{th} = 1.160 \times 10^{-4}$
Sersic $n = 4.81$
Black–NFW($m_2/m_1 = 1000$)
Green–Sersic
Red–Modified Hubble

$t/t_{th} = 3.329 \times 10^{-3}$
Sersic $n = 4.69$

$t/t_{th} = 5.916 \times 10^{-3}$
Sersic $n = 4.60$

$t/t_{th} = 7.091 \times 10^{-3}$
Sersic $n = 4.54$
Comparison with Observed Surface Brightness Distributions

Red: Core elliptical galaxies
Blue: Coreless

Data: Kormendy et al. (2009)
Inner concentration of the baryonic matter

- Formation of distinctive core composed of baryonic conglomerate through the core collapse.
- Total mass in this central concentration typically becomes $\sim$ a few $10^{-3}$ of the baryonic mass: close to SMBH?
Limitations of the current calculations

- Initial models are limited to the NFW profile only. General results and trends would be independent of the initial profiles.

- No further evolution of after the core-collapse: extension is possible by artificially adding an energy source to stop the collapse.

- Velocity distribution is isotropic. If substantial radial anisotropy among the baryonic conglomerates develops, the radial density profile could be modified.

  - Core–Halo structure (Spitzer 1987)

\[ \rho_{\text{halo}} \propto r^{-3.5} \]
Summary

- Dynamical friction could be effective if the early stars are preferentially formed in the form of massive clusters.
- The centrally concentrated systems can form quite rapidly ($\sim 0.01 \ t_\text{fh}$).
- The radial velocity anisotropy could modify the density profile in the outer parts.
- Mild rotation could be easily be incorporated, but may not change the results significantly.