The Kinematic Connection between Galaxies and Dark Matter Haloes

Aaron A. Dutton
(CITA National Fellow, University of Victoria)

Collaborators:
Charlie Conroy (Princeton), Frank C. van den Bosch (Utah), Surhud More (Chicago), Paco Prada (Granada), Luc Simard (HIA)
What is the behaviour of rotation curves at large radii?

NGC 3198

$2.2R_d$

$R_{200}$
Definitions

• **Optical Velocity: $V_{\text{opt}}$**
  Circular Velocity within “optical” region of galaxy:

  - For Late types (blue/disk dominated) $V_{\text{opt}} = V_2.2$ (rotation velocity at 2.2 exponential disk scale lengths)

  - For Early types (red/bulge dominated) $V_{\text{opt}} = V_{50} = 1.65\sigma_{50}$ (velocity dispersion within projected half light radius) (Padmanabhan et al. 2004, Wolf et al. 2009)

• **Virial Velocity: $V_{200}$**
  Circular velocity at virial radius ($<\rho>=200\rho_{\text{crit}}$) of dark matter halo.

\[ V_{\text{circ}}(r) = \left[ \frac{GM(<r)}{r} \right]^{1/2} \]
Why is $V_{\text{opt}}/V_{200}$ an interesting parameter?

- *Dynamical* link between galaxies and dark matter haloes
- Need to know $V_{200}$ to measure halo concentration, and compare with cosmological predictions
- Tells you something about global density profile of galaxies (e.g. can rule out isothermal, or NFW profile)
The Method

1. **Halo mass** (velocity) vs stellar mass from:
   - Weak Lensing (Mandelbaum et al. 2006, 2008; Schulz et al. 2010)
   - Satellite Kinematics (Conroy et al. 2007; More et al. 2010)
   - Group Catalog (Yang et al. 2007)
   - Abundance Matching (Moster et al. 2010; Guo et al. 2010; Behroozi et al. 2010)

2. **Optical velocity** vs stellar mass relations:
   - Tully-Fisher 1977 (Courteau et al. 2007; Pizagno et al. 2007)
   - Faber-Jackson 1976 (Gallazzi et al. 2006)

3. Cancel stellar mass to get (average) optical to virial velocity ratio: \( \frac{V_{opt}}{V_{200}} \)
Example 1.

- **Seljak 2002** applied this method for late type L* galaxies, using halo masses from weak lensing (Guzik & Seljak 2002).

- Derived $V_{\text{opt}}/V_{200} = 1.8$, and lower limit of 1.4 (95% CL)

- Naturally explained by LCDM halos + baryons + halo contraction (Navarro & Steinmetz 2000; Seljak 2002; Dutton et al. 2007)
Example 2.

- Eke et al. 2006 applied this method for late type galaxies, using halo masses from a group catalog.

- Derived $V_{\text{opt}}/V_{200} = 0.9-1.0$

- Not naturally explained by LCDM halos + baryons + halo contraction (Dutton et al. 2007)

To progress we need more accurate dark halo masses
Halo mass vs Stellar Mass

**Early types** (red/elliptical)

**Late types** (blue/disk)

Various data sets agree reasonably well

Error bars are 95% CL
Star formation is inefficient

**Early types** ($\varepsilon_{\text{SF}} < 10\%$)

**Late types** ($\varepsilon_{\text{SF}} < 25\%$)

Error bars are 95% CL
Halo mass ✨ Halo velocity

\[ \frac{V_{200}}{[\text{km s}^{-1}]} = \frac{R_{200}}{[\text{h}^{-1} \text{ kpc}]} = \left( \frac{G M_{200}}{[\text{h}^{-1} \text{ M}_\odot]} \right)^{1/3} \]

Halo velocity  Halo size  Halo mass

So the **halo mass - stellar mass** relation can be converted into a **halo velocity - stellar mass** relation
Velocity vs Stellar Mass

**Early types** (red/elliptical) | **Late types** (blue/disk)

Note: **Early types** have higher $V_{\text{opt}}$ (at fixed $M_{\text{star}}$) or lower $M_{\text{star}}$ (at fixed $V_{\text{opt}}$) than late types.
Velocity Ratio vs Stellar Mass

**Early types** (red/elliptical)  **Late types** (blue/disk)

- Points with error bars from Seljak (2002). Need to re-evaluate evidence for halo contraction (see later).
Early and Late type galaxies have remarkably similar $V_{\text{opt}} - V_{200}$ relations.

This is inspite of the different $V_{\text{opt}} - M_{\text{star}}$ and $V_{200} - M_{\text{star}}$ relations.

**A Universal Relation?**

Optical / Virial Velocity

Optical Velocity
Comparison with LCDM haloes

Using halo concentration-mass relation for dark matter haloes in WMAP5 cosmology (Maccio, Dutton & van den Bosch 2008)

• For LCDM haloes in WMAP5
  - $V_{\text{max},h} \approx 1.1 \, V_{200}$ (on average)

• For early and late types:
  - $V_{\text{max}} \approx V_{\text{max},h}$ (for $V_{200}=100$-$300$ km/s)

• For most massive early types:
  - $V_{\text{max}} < V_{\text{max},h}$
  optical galaxy only probes rising part of halo profile.
The Milky-Way (MW) and Andromeda (M31)

- $V_{2.2} = 220 \text{ km/s}$
- $M_{\text{star}} = 4.7-5.7 \times 10^{10} \ M_{\text{sun}}$
  (Klypin et al. 2002; Flynn et al. 2006; Hammer et al. 2007; Widrow et al. 2008)
- $M_{200} = 49-212 \times 10^{10} \ h^{-1} \ M_{\text{sun}}$
  (Klypin et al. 2002; Smith et al. 2007; Xue et al. 2008)

- $V_{2.2} = 260 \text{ km/s}$
- $M_{\text{star}} = 8.9-10.3 \times 10^{10} \ M_{\text{sun}}$
  (Klypin et al. 2002; Widrow et al. 2003; Hammer et al. 2007)
- $M_{200} = 137 \times 10^{10} \ h^{-1} \ M_{\text{sun}}$
  (Klypin et al. 2002)
• If current estimates of MW and M31 halo masses are Correct
  =>
  • MW and M31 do not have Typical $V_{opt}/V_{200}$
  • Must be significant scatter in $V_{opt}/V_{200}$ (might be hard to reconcile with small scatter in TF)
“Tully-Fisher” Relations

• MW and M31 do not fall on TF relation
  (this is known for the MW: Flynn et al. 2006; Hammer et al. 2007)
• High \( V_{\text{opt}}/V_{200} \) comes from both high \( V_{\text{opt}}(M_{\text{star}}) \) and low \( V_{200}(M_{\text{star}}) \)
A Simple Test for Galaxy Formation Models

- Current cosmological hydro simulations of galaxy formation predict higher $V_{\text{opt}}/V_{200}$ than observed (Abadi et al. 2003; Governato et al. 2007; Naab et al. 2007; Tissera et al. 2009; Piontek & Steinmetz 2009)

- Numerical Resolution is still important. A million particles per galaxy is not enough.
• Most simulations make too many stars.
• No simulations match both “TF” relations.
What is the behaviour of rotation curves at large radii?
Rotation curves are almost flat out to virial radius!
What constraints does $V_{\text{opt}}/V_{200}$ place on the structure of dark matter halos?

Preliminary!
**Bulge-Disk-Halo models**

Exponential Disk, Hernquist Bulge, NFW Halo

**7 Parameter Mass Model**
Baryons: $R_d$, $R_b$, B/T, $M_{\text{star}}$
Dark Matter: c, $V_{200}$, halo response

**7 Constraints**
1. $R_d$, $R_b$, B/T from bulge+disk fits to 100k SDSS galaxies
2. $M_{\text{star}}$ from Bell et al. 2003 -0.1 dex (Chabrier IMF)
3. Tully-Fisher / Faber Jackson relations
4. $c$-V$_{200}$ relation from LCDM Nbody simulations
5. $V_{\text{opt}}$/$V_{200}$ relation

Model is fully constrained
=> Solve for halo response to galaxy formation

Without $V_{\text{opt}}/V_{200}$ Model is Degenerate

$V_{2.2} = 224$ km/s
Dark Halo Concentration - Mass Relation

Definition: \( c = \frac{R_{200}}{r_2} \) (virial radius / NFW scale radius)

- Lower mass haloes have higher concentration (NFW97, Bullock et al. 2001)
- Small scatter \( \sim 0.1 \text{dex} \) in concentration (Wechsler et al. 2002; Maccio et al. 2007)
- Zero point (and slope) depends on cosmological parameters (e.g. Eke et al. 2001; Maccio, Dutton & van den Bosch 2008)
- Here use concentration-mass relation in WMAP5 cosmology (Maccio, Dutton & van den Bosch 2008)
Dark Halo Concentration - Mass Relation

Definition: \( c = \frac{R_{200}}{r_2} \) (virial radius / NFW scale radius)

- **Late types** are consistent with LCDM prediction
  => But no room for halo contraction
  (see also Dutton et al. 2007)

- **Early types** have concentrations factor
  \(~2.5\) higher than predicted
  => Evidence for halo contraction
  (see also Schulz et al. 2010)
Dark Halo Concentration - Mass Relation

Definition: \( c = \frac{R_{200}}{r_2} \) (virial radius / NFW scale radius)

Changing cosmology cannot Reconcile early and late-types

- **Late types** are consistent with LCDM prediction
  => no room for halo contraction (see also Dutton et al. 2007)

- **Early types** have concentrations factor ~2.5 higher than predicted
  => Evidence for halo contraction (see also Schulz et al. 2010)
Dark Halo Concentration - Mass Relation

Definition: $c = \frac{R_{200}}{r_2}$ (virial radius / NFW scale radius)

Stellar IMF or Halo Response is Not Universal

- **Late types** are consistent with LCDM prediction
  => no room for halo contraction (see also Dutton et al. 2007)

- **Early types** have concentrations factor ~2.5 higher than predicted
  => Evidence for halo contraction (see also Schulz et al. 2010)
Central densities of dwarf & LSB galaxies are consistent with predictions of LCDM-WMAP5 cosmology

Mean density (wrt critical) of halo within radius where $V_{\text{circ}}$ is half $V_{\text{max}}$ (Alam, Bullock & Weinberg 2002)

For an NFW halo $V_{\text{max}}$ occurs at $2.163\, r_s$

$\Delta_{V/2}$ is equivalent to NFW concentration parameter, ASSUMING $V_{\text{max}}$ observed = $V_{\text{max}}$ of halo
Summary

• We derive the mean relation between optical ($V_{\text{opt}}$) and virial velocities ($V_{200}$) of early and late type galaxies at $z=0$.

• Early and Late-Type galaxies may follow the same relation

$$V_{\text{opt}} \approx V_{\text{max, h}} \approx 1.1 \, V_{200} \text{ for } 100 < V_{\text{opt}} < 300 \text{ km/s}$$

• The MW and M31 appear to have higher $V_{\text{opt}}/V_{200}$ than typical spirals

• The $V_{\text{opt}}/V_{200}$ ratio is not currently reproduced by cosmological hydro simulations of galaxy formation

• Mass models favor no halo contraction in late-types, standard halo contraction in early types.