Dwarf Galaxy Rotation Curves: A Problem for Cold Dark Matter?  

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Happy Birthday Bernard!
Spiral Galaxy NGC 253
Measuring Masses of Galaxies

- Use Newton’s Law \( M(R) = \frac{V^2 R}{G} \)
- Measure rotation using:
  - atomic hydrogen 21-cm line
  - ionized gas emission lines
  - doppler shift of stellar absorption lines
Dwarf Galaxies and Cosmology

Are they the oldest stellar systems?

Are they building blocks for larger galaxies

What is their star formation history?

Can we observe them at high redshift?

What Constraints do they place on CDM?
Galaxy formation and dark matter

Galaxies form in potential wells of dark matter halos

What form do the density profiles of halos have, and why?

Navarro Frenk and White (1997) find density profiles can be fit by one functional form

Key feature is the formation of a cusp in density at the halo center

Is this seen in galaxy and galaxy cluster density profiles?
Rotation Curves

Tilted ring model: galaxy as a set of concentric rings

\[ V(x, y) = V_0 + V_c(R) \sin(i) \cos(\theta). \]

\[ \cos(\theta) = \frac{-(x - x_0) \sin(\phi) + (y - y_0) \cos(\phi)}{R} \]

\( \phi \) is the inclination angle of the galaxy

\( V_0 \) is the systemic velocity of the galaxy

\( \theta \) is the azimuthal angle in the plane of the galaxy

\( R \) mean radius of the ring in the plane of the galaxy

\( V_c(R) \) is the rotation curve

Density Profile from rotation curve

\[ \rho(r) = \frac{2v}{r} \frac{\partial v}{\partial r} + \left(\frac{v}{r}\right)^2 \]

galaxy is dark matter dominated and symmetric
Simulations

Gasoline Code: SPH + gravity + star formation + feedback

\[ N_{\text{dark}} = 1.6 \times 10^6 \]

\[ N_{\text{gas (initial)}} = 2 \times 10^5 \]

\[ N_{\text{star (initial)}} = 2 \times 10^5 \]

force resolution 60 pc

\[ M_{\text{disk}}/M_{\text{halo}} = 0.025 \]

Age = 1 Gyr
simulation dwarf barred galaxy

face on view cold gas (T<15000 K)  
stellar component
Velocity curves for barred dwarf model

- --- circular velocity
- - - stellar rotation
- -- - cold gas
Why is $V_{\text{circ}} > V_{\text{rot}}$ for the gas in the simulations?

- $V_{\text{circ}}$ cold gas
- $V_{\text{rot}}$

△ recovery of $V_{\text{circ}}$ from $V_{\text{rot}}$
using asymmetric drift correction

feedback is partially responsible
Why is $V_{\text{circ}} > V_{\text{rot}}$ for the gas in the simulations?

Feedback contributes $\sim 10\%$ effect.

Projection effects contribute an additional $\sim 10\%$.

Additional effects: random bulk velocities and pressure gradients.

$$
V_c^2 = V_{\text{rot}}^2 - \sigma_r^2 \left( \frac{\partial \ln \Sigma}{\partial \ln R} + \frac{\partial \ln \sigma^2}{\partial \ln R} - \beta \right) + \frac{kT}{\mu m_H} \left( \frac{\partial \ln \Sigma}{\partial \ln R} + \frac{\partial \ln T}{\partial \ln R} \right)
$$

All of these terms are important! Observers underestimate $\sigma_r$ (e.g., use 6 km/s). It is crucial to get this number right.
Recovering the circular velocity in the model with star formation and a bar

--- $V_{\text{circ}}$

----- $V_{\text{rot}}$

--- circular velocity recovery using only the gas pressure gradient

$x$ asymmetric drift correction assuming constant rms velocity of 6km/s

▲ circular velocity recovery with all the terms included
Case Studies:
NGC 3109 and NGC 6822

<table>
<thead>
<tr>
<th>morphological type</th>
<th>SBm</th>
<th>IBm</th>
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<tbody>
<tr>
<td>distance</td>
<td>1.4 Mpc</td>
<td>0.5 Mpc</td>
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<tr>
<td>inclination</td>
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<td>60°</td>
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<tr>
<td>maximum vrot</td>
<td>67 km/s</td>
<td>55 km/s</td>
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</table>
NGC 3109 Velocity field and H-alpha image
NGC 3109 Rotation Curve
Blais-Ouelette (2002) NGC 3109 mass model
H-alpha and HI beyond 2.7 kpc

![Graph showing velocity (V) vs. radius (kpc) for NGC 3109, ISO, KKBP, Burkert, and NFW models.]
NGC 3109
Isophote fit to I Band data, Jobin (1990)
NGC 3109: note variations in inclination and position angle isophotes with radius
NGC 6822  Case Study
local group dwarf irregular barred galaxy
Weldrake, de Blok and Walter (2002) tilted ring model fits, high resolution HI data

![Graph showing PA, i, V_\text{rot} vs. radius (arcsec)]
NGC 6822 derived rotation curve and CDM fit
Weldrake, de Blok and Walter (2002)

\[
\begin{align*}
NFW HALO & \Lambda CDM \\
c & = 9.50 \pm 0.12 \\
V_{200} & = 52.41 \pm 0.00 \text{ km s}^{-1} \\
(M/L)(K_s) & = 0.00 \pm 0.00 \\
\chi^2_{red} & = 1203.09
\end{align*}
\]
NGC 6822: derived density profile

--- minimum disk NFW model

___ best fit pseudo isothermal model
• Our approach: analyze N-body simulations of disks rotating in an NFW halo

• We do a tilted ring model analysis on the Nbody simulation just like the observers

• the goal is to understand observational biases including projection effects and the effect of known features such as bars and bulges on the inferred mass distribution
Understanding Projection Effects

Two lines of sight through a galaxy disk 0.7 and 4.1 kpc
Case study NGC 3109: barred galaxy model viewed with inclination 75°
Edge on bar model
Isophotes and surface brightness profiles contain useful information.
Bar (upper) no bar (lower)
Effect of Bar on the measured density profile

\[
\log(\rho/[M_\odot pc^{-3}]) = -0.5 \\
\log(R/kpc) = -2.5 \\
\log(\rho/[M_\odot pc^{-3}]) = -1 \\
\log(R/kpc) = -0.5
\]
NGC 3109 rotation curve

- Data
- (upper) circular velocity
- (lower) rotation velocity measured by an artificial observer
NGC 3109 photometry

**surface brightness I-band**
- ••• data
- — model
NGC 3109 isophotes

Model

I band data
NGC 3109 isophote position angle and inclination

--- HI data
— model
... I band isophotes
▲ Hα data
NGC 3109 model

- - - halo contribution
...... disk contribution
___ total circular velocity

$V_c$ km/s vs. $r$ kpc
NGC 6822 rotation curve

- data
- (upper) circular velocity
- (lower) rotation velocity measured by an artificial observer
NGC 6822 photometry

surface brightness I-band

••• data

— model

\( \mu_k \) (mag/arcsec\(^2\))

\( r \) (kpc)
Surface density and isodensity contours for our model position angle between bar and major axis consistent with Cioni & Habing observations (2005)
NGC 6822 model photometry

--- HI data
— model
NGC 6822 model

- - - halo contribution
...... disk contribution
___ total circular velocity

$V_c$ km/s

$r$ kpc
Stellar and Gas Rotation velocities (NMSU APO data)

--- absorption lines

..... emission line data
Non-circular motions

LSB DDO 39 Swaters et al (2003). H-alpha imaging tilted ring analysis at various radii. NFW consistent with the data but core also

0.2-0.7 kpc

1.7 - 2.3 kpc
Conclusions

- Rotation curves alone are not enough to resolve the issue
- Need extra data such as surface photometry
- One must analyze non-circular motions in the data, e.g., using higher order moments
- Ideal data are velocity dispersion at each position
- Need observations of gas and stars to understand dynamics
- Need more theory: adiabatic contraction versus bar effect