The Dark Matter Halos of LSB Galaxies

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The Dark Matter Halos of LSB Galaxies:  

The Cusp-Core Problem
Expectations
### Expectations from Simulations of Cold Dark Matter

CDM halos are “cuspy”: steeply rising density profiles

\[
\rho \sim r^{\alpha}
\]

<table>
<thead>
<tr>
<th>(\alpha)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>NFW (1996, 1997)</td>
</tr>
<tr>
<td>-1.5</td>
<td>Moore et al. (1999)</td>
</tr>
<tr>
<td><strong>Mass dependent</strong></td>
<td>Reed et al. 2003</td>
</tr>
<tr>
<td><strong>Radius dependent</strong></td>
<td>Navarro et al. 2004</td>
</tr>
<tr>
<td>little less than -1</td>
<td>Navarro et al. 2008</td>
</tr>
<tr>
<td>+ others ...</td>
<td></td>
</tr>
</tbody>
</table>
Shapes of CDM Halos

- **Spherical**: $a = b = c$
  - all three equal

- **Prolate**: $a > b = c$
  - one long axis
  - football

- **Oblate**: $a = b > c$
  - one short axis
  - frisbee

- **Triaxial**: $a > b > c$
  - three different
Shapes of CDM Halos

CDM halos are triaxial and more often prolate than oblate (e.g. Allgood et al. 2006)

CDM halos have axis ratios that change with radius; triaxial at the center, spherical near the edge (Hayashi et al. 2007)

(Hayashi, Navarro & Springel 2007)
Cuspy NFW Halos

\[ \Phi(R) = -\frac{GM_{200} \ln(1 + R/R_s)}{R \left[ \ln(1 + c) - c/(1 + c) \right]} \]

- fast-rising rotation curves
- pinched velocity fields
Observations of Dark Matter-Dominated Galaxies
Observations of Dark Matter-Dominated Galaxies

Low Surface Brightness Galaxies

- dark matter-dominated down to small radii
- zero/minimum disk assumption about baryonic mass
Radio Data: HI Observations

HI Velocity Fields and Rotation Curves:

Moore (1994)
Flores & Primack (1994)
de Blok, McGaugh, & van der Hulst (1996)
+ many more ...

\[ \rho \sim r^{-1.8} \]
\[ \rho \sim r^{-1} \]
\[ \rho \sim r^0 \]

Flores & Primack (1994)
Optical Data: Long-slit Hα Observations

Long-Slit Hα Rotation Curves:

McGaugh, Rubin, & de Blok (2001)
de Blok & Bosma (2002)
Marchesini et al. (2002)
+ many more ...

- $\rho \sim r^{-1.5}$
- $\rho \sim r^{-1}$
- $\rho \sim r^0$

Marchesini et al. (2002)
Observations of Dark Matter-Dominated Galaxies

\[ \rho \sim r^{-1} \]

\[ \rho \sim r^{0} \]

de Blok & Bosma (2002)

NFW

SLOPE \( \alpha \)

de Blok, Bosma & McGaugh 2003
**Observations of Dark Matter-Dominated Galaxies**

**Inconsistencies:**
- Rotation curve shapes
- Halo parameters
- Cosmological parameters

The Cusp-Core Problem

Expect *cusps*, but observe *cores*

\[ \rho \sim r^0 \]

Pseudo-Isothermal Halo

No Cosmological Motivation
No Theoretical Basis

roughly constant

Cored halo
A Problem with the Data?

HI Rotation Curves

Low spatial resolution?

Long-Slit Hα Rotation Curves

Slit misplacement?

Noncircular motions?

- New Observational Approach -

Integral Field Spectroscopy

well-resolved optical velocity fields

sub-kiloparsec resolution

two-dimensional data

Kuzio de Naray et al. (2006, 2008)
Chemin et al. (2004)

Swaters et al. (2003)
Simon et al. (2005)

+ others ...
Integral Field Spectroscopy with the DensePak IFU
Observing with DensePak

43" x 28" fixed array of 3" fibers
Observing with DensePak
Observing with DensePak
Observing with DensePak

Wavelength

Fibers

[Si II] 671.7, 673.1

[N III] 658.4

Hα

Sky
Observing with DensePak

Δλ = Δvelocity in Halpha

[HII] 6584

No Δλ in Sky

Sky

Fibers

Wavelength
Observing with DensePak

Observing with DensePak
IFU Velocity Fields

Kuzio de Naray et al. (2006, 2008) – DensePak

Swaters et al. (2003) – SparsePak

Chemin et al. (2004) – FaNTOmM

Simon et al. (2005) – DensePak
Comparison with Previous Observations

**F 568-3**

- **DensePak**
- **Long-slit**
- **HI**

**UGC 1281**

Kuzio de Naray et al. (2006)

Broad consistency with previous long-slit and HI rotation curves.
Halo Fits: Cuspy NFW

For 17 galaxies in Kuzio de Naray et al. (06, 08):

No NFW fit possible or concentration too low for majority of galaxies

<table>
<thead>
<tr>
<th>Source</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>median Dpak</td>
<td>$c \sim 4.5$</td>
</tr>
<tr>
<td>Tegmark 04</td>
<td>$c \sim 8.2$</td>
</tr>
<tr>
<td>WMAP3</td>
<td>$c \sim 6.1$</td>
</tr>
</tbody>
</table>

Concentrations that are $\sim 2 - 2.5$ $\sigma$ low:

- Gentile et al. (2007) – problematic
- Swaters et al. (2003) – less concerned

Concentrations decrease when zero disk assumption is relaxed.
Halo Fits: Rotation Curve Shapes

Kuzio de Naray et al. (2006)

Gentile et al. (2005)
Halo Fits: Cored Profiles

For 17 galaxies in Kuzio de Naray et al. (06, 08):

13 of 17 galaxies best-described by isothermal halos

Core radius is typically a few kpc
Can Noncircular Motions Solve the Problem?

\[ 3\sigma^2 = V_{CDM}^2 - V_{DM}^2 \approx 20 \text{ km/s} \]

\[ \sigma_{\text{observed}} \approx 6 - 10 \text{ km/s} \]
Can Noncircular Motions Solve the Problem?

Harmonic decomposition of velocity field

\[ V_{LOS} = c_0 + \sum_{m=1}^{N} [c_m \cos(m\psi) + s_m \sin(m\psi)] \]

Rotation velocity  Radial velocity

NGC 2366

Trachternach et al. (2008)
Noncircular Motions

Noncircular motions in 19 THINGS galaxies (Trachternach et al. 2008)

Median $\sigma$ (km/s)

Average $\sigma$: 6.7 km/s

~90% of galaxies $\sigma \leq 9$ km/s

M_B Hubble Type $\log(M_{bar}/M_{tot})$

Elongation of potential

$<\epsilon_{pot}> = 0.017$

pretty round
Modeling the DensePak Data

- Two-dimensional rigid analytic NFW potential

- Halo parameters consistent with the cosmological concentration-$V_{200}$ relation

- Observed disk scale length, inclination spatial resolution, velocity dispersion

- “Observe” the simulated galaxies with the DensePak IFU
Non-Axisymmetric Potential

*Noncircular Orbits*

Fixed axis ratios:
[similar to Hayashi et al. (2007)]

\[ q = 0.98 \quad 0.90 \]
\[ 0.96 \quad 0.88 \]
\[ 0.94 \quad 0.86 \]
\[ 0.92 \quad 0.84 \]

Angle between elongated axis and line-of-sight:

\[ \phi = 0^\circ, 30^\circ, 45^\circ, 60^\circ, \text{ and } 90^\circ \]

These 2D potentials are equivalent to 3D prolate dark matter halos in which the long axis of the halo coincides with the elongated axis of the disk.
Non-Axisymmetric Potential

\[ \phi = 0^\circ \] \hspace{2cm} \[ \phi = 45^\circ \] \hspace{2cm} \[ \phi = 90^\circ \]

Asymmetric Halo

Mock rotation curves both above & below the true circular rotation curve
Non-Axisymmetric Potential

May need an axis ratio that changes with radius, however ...

Inconsistent with random distribution of halo orientations on the sky

Elongated axis $\perp$ to observer’s LOS

barred galaxy
Triaxial Halo

Tobias Kaufmann (UCI): 3D simulations with gas and dark matter

Triaxial velocity fields show the “NFW pinch” that is not seen in observed velocity fields
Summary

- Numerical simulations predict **cuspy, prolate-triaxial** halos with **pinched velocity fields** and **fast-rising rotation curves**

- **Observed** LSB HI & long-slit rotation curves are **more consistent** with **cored** halos

- Velocity fields from **IFU spectroscopy** look **solid-body** & rotation curves are also better-described by **cored** halo profiles

- Noncircular motions typically **not large enough** to reconcile the data with cuspy halos

- **2D simulations:**
  - may indicate the need for radially-varying axis ratio
  - **BUT** special viewing angle required (φ → 90°)

- **3D simulations:**
  - Triaxial Halo → mock DensePak velocity fields look pinched