Kinematics of LSB and Dwarf Galaxies: Implications for LCDM Models

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with Anatoly Klypin NMSU Octavio Valenzuela UNAM and Fabio Governato UW
the rotation curve
example of spiral galaxy data

NGC 891
\[
\frac{GM(< r)}{r^2} = \frac{v^2}{r}
\]
4.4 billion particles per halo

cusp is present between 0.2 and 1 kpc with slope steeper than -1
Bars can modify the structure of the halo

linear theory

N-body

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\( \rho \) vs. \( r \) (units of bar radius)

(a) Bar rotations: 0, 1.1, 3.5, 4.6, 5.8, 6.3

(b) Bar rotations: 0.0, 1.1, 3.5, 4.6, 5.8, 6.3
Dynamical friction of sub-clumps of baryons heats up halo overcomes adiabatic contraction effect and creates a core

Random bulk motions induced by stellar feedback can heat up the dark matter distribution removing the cusp.

The blue, green and red lines simulated halo after 40, 80 and 140 Myr, dotted line marks the radius $A = 400$ pc (the amplitude of the oscillations).

The efficiency of the various mechanisms outlined above (to remove the cusp) versus adiabatic contraction (to enhance the cusp) is still an open question...
The real world
\[ V_t(r, \theta) = \bar{V}_t(r) + \sum_{1}^{\infty} V_{m,t}(r) \cos[m\theta + \theta_{m,t}(r)] \]

\[ V_r(r, \theta) = \bar{V}_r(r) + \sum_{1}^{\infty} V_{m,r}(r) \cos[m\theta + \theta_{m,t}(r)] \]

\[ V_{\text{obs}} = V_{\text{sys}} + \sin i(V_t \cos \theta + V_r \sin \theta) \]
Is H-alpha gas a good tracer of the potential?

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Pizzella et al integral field spectroscopy of 3 LSB galaxies with VMOS VLT

velocity residuals from rotation curve fit are substantial!
compare gas (red) vs stars (black) along LSB minor axis
can we quantify non-circular motions?

eg: for bar symmetry use m=2 terms

\[ V_{\text{model}} = V_{\text{sys}} + \sin i \left[ \bar{V}_t \cos \theta - V_{2,t} \cos(2\theta_b) - V_{2,r} \sin(2\theta_b) \sin(\theta) \right] \]

\[ \theta_b = \theta - \phi_b \]

\( \phi_b \) is the bar position angle

most spiral galaxies are barred
Apply to NGC 2976 Spekkens & Sellwood 2007
The HI Nearby Galaxy Survey

19 nearby $3 < D < 15$Mpc disk galaxies at high spatial and velocity resolution
THINGS approach to non-circular motions

\[ V_{\text{los}}(r) = V_{\text{sys}}(r) + \sum_{m=1}^{3} c_m(r) \cos m\theta + s_m(r) \sin m\theta \]

\[ \epsilon_{\text{pot}} \sin(2\varphi_2) = (s_3 - s_1) \frac{1 + 2q^2 + 5q^4}{c_1(1 - q^4)} \quad q = \cos(i) \]

\( \varphi_2 \) is the angle between the minor axis of the elongated ring and the observer

n.b. epicycle theory applies to gas on closed orbits and small distortions
Spitzer irac 3.6 micron

HI map VLA

PV diagram major axis

PV diagram minor axis

Spitzer irac 3.6 micron

HI map VLA
eg ngc 3198

residuals to the tilted ring fit
white -30km/s to +30km/s black

\begin{figure}
\centering
\includegraphics[width=\textwidth]{n3198}
\caption{Residuals to the tilted ring fit for ngc 3198. The white line represents residuals from -30 km/s to +30 km/s.}
\end{figure}
intensity weighted mean velocity  -24.3 km/s

maximum velocity  -36.8 km/s

NGC 6822
NGC 6822 semi major axis 0.5kpc

position angle

radial velocity

0

20

10

0

-10

-20

0  100  200  300

position angle
ngc 6822 residuals from circular rotation fit
where do we go from here?

1. we need better theoretical predictions: DM simulations predict a cusp on the scale 0.1~1 kpc but what about the effects of baryons?

2. when comparing models to data try to use models that more closely match real galaxies (eg Governato’s talk) rather than epicycle approximation which may not apply

3. As well as using different data sets, examine the same data sets eg NGC 6822 (Rhee et al in prep) so we can reach agreement on the amplitude of non-circular motions and how best to measure them

4. Given difficulties with gas, try to obtain rotation curves of galaxies using optical emission from the stars (difficult but worth the effort)