Angular momentum of dwarf galaxies

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Angular momentum (AM)

- Mass and AM are fundamental parameters.
- AM in galaxies is originated from tidal torques between neighbouring halos. (Peebles 1969)
- Models predict specific angular momentum \((j)\) of halo \(j_{H} \propto \frac{M_{H}^{2/3}}{}\)
- Baryons and dark matter acquire identical AM initially. (van den Bosch et al. 2002)
Observations

- Stellar $j_\ast$ & $M_\ast$ follow $j_\ast = kM_\ast^{2/3}$, with ellipticals have 5x lower than spirals. (Fall 1983; Romanowsky & Fall 2012)

- Baryonic $j_b$ and mass $M_b$ correlate with bulge fraction ($\beta$), $j_b \propto M_b$ for a fixed $\beta$. (Obreschkow & Glazebrook 2014)

- Dwarfs lie above $j_b$-$M_b$ relation for bulge-less spirals. (Butler et al. 2017, Chowdhury & Chengalur 2017)
Environmental dependence?

• What are the physical processes that determine AM?
  - e.g. tidal torques, feedback, accretion, and stripping
• Different processes dominate in different environments →
  Investigate environmental dependence of $j_b$-$M_b$ relation.
Environmental dependence?

- What are the physical processes that determine AM?
  - e.g. tidal torques, feedback, accretion, and stripping
- Different processes dominate in different environments → Investigate environmental dependence of $j_b-M_b$ relation.
- Sample: 11 galaxies from Lynx-Cancer void.
- AM is calculated using the HI kinematics (GMRT, VLA) and SDSS images.
Results: $j_b$-$M_b$ relation for dwarfs

*Kurapati et al. 2018*

j$_b$ of dwarfs in void is similar to dwarfs in field.

Field dwarfs -> Butler et al. 2017, CC 2017
Results: $j_b$-$M_b$ relation for dwarfs

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\[
\begin{array}{|c|c|c|}
\hline
\text{Galaxy} & \text{Slope} & \text{Intercept} \\
\hline
\text{Spirals} & 0.94 \pm 0.05 & -0.13 \pm 0.04 \\
\text{Dwarfs} & 0.89 \pm 0.05 & 0.40 \pm 0.08 \\
\hline
\end{array}
\]

$j_b$ of dwarfs in void is similar to dwarfs in field.

Dwarfs have higher $j_b$ compared to bulge-less spirals.
Stability model

- If \( j \) is regulated by stability criterion, 
  \[ j \propto M \times (\sigma/Q)^{-1}, \]
  where \( \sigma \) is velocity dispersion.
  
  (Zasov & Zaitseva 2017)

Best fit value of \( \sigma/Q \) is 2.8 km/s;
matches to canonical values of \( \sigma \) (6-10 km/s) and \( Q \) (2-4)
Dwarfs versus spirals

\[ M_b \sim 10^{9.1} \, M_\odot, \]

similar to thickening of gas discs.

\[ \text{Angular momentum of dwarf galaxies} \]
Stellar feedback

- Increase in $j_b$ sets at $M_b \sim 10^{9.1} M_\odot$, which is similar to thickening of gas discs.

- Stellar feedback might be responsible for both increase $j_b$ and thickness of discs.

- Quantitatively, star formation in dwarfs is insufficient to increase in $j_b$ for a marginally stable disc.
Summary

- Dwarfs in voids and field have similar $j_b$ values.

- $j_b$-$M_b$ slope is consistent with marginally stable disk.

- Dwarfs have higher $j_b$ values than bulge-less spirals.

- Increase in $j_b$ sets at $M_b \sim 10^{9.1}M_\odot$, which is similar to thickening of gas disks.

- Stellar feedback processes are probably responsible; SF may not be sufficient to produce the observed increase in $j$. 
Additional slides
Dwarfs in UM have similar $j$ as dwarfs in other densities.

Spirals in UM have lower $j$ compared to spirals in other densities.
Stability model

- Local instabilities could lead to star formation, which may lead to outflows. The remaining material adjusts itself so that the disk is marginally stable.

- The stability condition against gravitational perturbations is characterized by Toomre $Q$.

- In case of a thin disc, critical value is $Q = 1$. Non-zero thickness of a disc makes the disc more stable.

- If the $j$ is regulated by stability criterion, $j = M \times (QG/4\sigma)$. Where, $\sigma$ is the velocity dispersion.
Rotation curves

Tilted ring model was fit to HI data cube using FAT (3D)

(Rogstad et al. 1974)
Sample

- Lynx-Cancer void (D \sim 18 \text{ Mpc}), consists of 103 faint galaxies. (Pustilnik et al. 2011)

- 25 gas-rich galaxies (M_{HI}/L_B > 1.9, M_B > -16) were selected.

- To get good rotation curves, galaxies with
  - well behaved velocity fields
  - at least 6 beams across the major axis
  - inclinations greater than 35^0 were selected.

- The galaxy KK246 from Tully void is also included → 11 galaxies
Angular momentum Catastrophe

- Disks in simulations show are an order of magnitude smaller.
- Gas loses significant angular momentum to dark matter due to “over-cooling”.

![Graph showing relation between Log $J_{\text{axis}}$ and Log $V_{\text{rot}}$]
Angular momentum catastrophe-solution

- The problem diminished in the models which include baryonic feedback such as
  - Stellar winds
  - Supernovae feedback
- Outflows can preferentially remove low angular momentum gas.

E.g. Gas outflows from M 82

Image credits: J. Gallagher, M. Mountain and P. Puxley
Cold-mode accretion

- Flows along filaments
- Carries more AM
- Dominant in low-mass haloes.

Stewart et al. 2013
Is feedback sufficient?

- Assuming
- If we assume all material within a fractional radius $\alpha$ is lost,
  - Mass will decrease by a factor of $(1-\alpha)$
  - Offset in $j_b-M_b$ plane will increase by $\log((1+\alpha)/(1-\alpha))$
Angular momentum

- Tidal torquing in early universe: \( j_H = k M_H^{2/3} \)

- At early epochs, \( j_b^0 = j_H \)

- Baryon to dark matter fraction: \( f_b = M_H / M_b \)

- Angular momentum retention fraction \( f_j = j_b^0 / j_b \)

- Then, \( j_b \propto f_j f_b^{-2/3} M_b^{2/3} \)

\( j_H, \ j_b \) are sAM of dark matter halo, baryons.

\( M_H, \ M_b \) are mass of dark matter halo, stars and baryons.
Sample

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- The galaxy
  \rightarrow 11 \text{ galaxies}
Tilted Ring Model

- Rotation curves can be derived by fitting a tilted ring model; assumes gas is confined to a thin disk and is in circular motion (Warner et al. 1973).
- A set of concentric rings is used to describe the motion of gas; each ring has a constant rotation velocity $V_{rot}$, depends only on mean radius.
- Each ring is characterized by an inclination $i$, a position angle (PA) of major axis projected onto sky $\Phi$. If $V_{sys}$ is systematic velocity, $\theta$ is PA in plane of galaxy, then line of sight velocity at any point $(x,y)$ is:

$$V(x, y) = V_{sys} + V_{rot} \sin(i) \cos(\theta)$$

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

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