Angular Momentum in Halos & Galaxies

- Tidal torque theory
- Halo spin
- The angular momentum distribution in halos
- Gas condensation & Disk formation
- The AM problems
- gas AM vs dark matter AM

how do galaxies get their spin?

the spin parameter
Origin of Angular Momentum

Tidal Torque Theory (TTT):
Peabody 1976 White 1984

Result:
\[ I \propto \int \phi d^3 q \]

Tidal:
\[ \frac{\partial \phi}{\partial q} \frac{\partial \phi}{\partial q} \] Inertia:
\[ I = \int \rho \phi^2 d^3 q \]

angular momentum in protohalos grows linearly with time.

Tidal Torque Theory

angular momentum in Eulerian patch comes from gravitational coupling of the quadrupole moment of the protohalo’s mass distribution with the tidal field. torque depends on the misalignment.

Porciani, Dekel & Hoffman 02

Stages in Halo Formation

first collapse along major axis of inertia & tidal field filament breaks into clumps. clumps merge.

Porciani, Dekel & Hoffman 02

Proto-halo: a Lagrangian patch
halo spin parameters

\[ \lambda \equiv \frac{J E^{1/2}}{G M^{5/2}} \]
\[ \lambda' = \frac{J}{\sqrt{2 M V R}} \]

Peebles 76
Bullock et al 01

approximately: rotational support in units of the virial velocity dispersion

- typical values are 0.02-0.11

distribution of the spin parameter

\[ \lambda' = \frac{J}{\sqrt{2 M V R}} \]

doesn’t depend on M, z, cosmology

Bullock et al 01

Barnes & Efstathiou 87, Ryden 88, Warren et al 92, Steinmetz & Bartelman 95, Cole & Lacey 96, Gardner 01, Bullock et al 01, Maccio et al 06
angular momentum growth through mergers

basic picture: growth of spin in halos is a random walk
much of spin-up comes from a sequence of minor mergers

angular momentum growth through mergers

quiet halos with no recent major merger

angular momentum growth through mergers

angular momentum growth through mergers
angular momentum profiles

A two-parameter family: spin & shape

\[ M(<j) = M_v \frac{\mu j}{j_0 + j} \]

High spin halos have J more evenly distributed

Bullock et al. 01

radial profile of j

~10% have significant misalignment between shells

Bullock et al. 01

basic picture

Morphology is a transient feature of galaxies set by its merging history.
Disks are formed during quiet periods.

Maller, Dekel & Somerville 02
classic disk formation picture

- gas initially well mixed in a smoothly rotating halo
- angular momentum exists due to tidal torques
- falls in to form an angular momentum-supported exponential disk
- assumes that the specific angular momentum of the disks are the same as their host halos

Fall & Efstathiou 1980, Blumenthal et al 1986, Mo, Mao & White 1998

classic disk formation picture

- gas initially well mixed in a smoothly rotating halo
- mass of the disk is a fixed fraction of the halo mass
- angular momentum is a fixed fraction of the halo AM
- disk is thin with an exponential surface density
- only dynamically stable systems can be disks.
- falls in to form an angular momentum-supported disk
- gives an estimate for the sizes & rotation curves of disks

Mo, Mao & White 1998

Disk Profile from the Halo J Distribution

Assume the gas follows the halo J distribution
Assume conservation of J during infall from halo to disk.
In disk: lower J at lower r

\[ M_{\text{halo}}(\mu) = M_{\text{inj}} \frac{j}{j_0+j} \mu \geq 1 \]

falling in to form an angular momentum-supported exponential disk

\[ M_{\text{inj}}(\mu) = f_j M(\mu) \]

\[ j(r) = V_r \sqrt{\frac{G M(r)}{r}} \]

\[ M_{\text{halo}}(\mu) \rightarrow m_{\text{halo}}(r) \]

\[ m_j(r) = f_j m_r M(\mu) \frac{j(r)}{j_0+j(r)} j(r) < j_{\text{max}} \]

\[ M_0 = r_0 V_0 \]

Assume isothermal sphere
No adiabatic contraction

\[ m_j(r) = f_j m_r M(\mu) \frac{r}{r_0 + r} \]

\[ \Sigma_j(r) = f_j m_r M(\mu) \frac{r}{2\pi} \frac{r_0}{r(r_0 + r)} \]

basic picture

- r^2 radiative cooling
- merger
- accretion
That's all well and good.
But does it have anything to do with galaxies?

A perpetual problem to form realistic disk galaxies in cosmological simulations

The Spin Catastrophe

observations simulations

Dynamical components of a simulated galaxy

basic picture, that the various components are set by the merging history is probably right.
angular momentum problems

- the observed spin component of galaxies is comparable or larger to that of dm halos, but cooling of the baryons should make it smaller
- baryons in observed dwarfs seem to lack the low-j and high-j tails of the distribution of angular momentum for dark halos

are DM & galaxy J really the same?

not likely.
see van den Bosch et al 02, Wise & Abel

although the two components experience the same torques and the same merging processes, they undergo very different relaxation, heating, etc.
dm: violent relaxation; gas: shock heating + feedback

remember, standard model assumes specific angular momentum conservation
if cooling is the problem, maybe heating is the solution...

\[ E_{SN} \approx v_e \dot{M}_e t_{rad} \propto M_* \left( \frac{t_{rad}}{t_H} \right) \]
\[ M_* = M_* / t_H \]
\[ E_{SN} = M_{\text{gas}} V^2 \]

\[ \rightarrow V_{\text{crit}} = 100 \text{ km/s} \quad M_{*\text{crit}} = 3 \times 10^{10} M_\odot \]

feedback in satellite halos

in small satellites heating can blow out gas, low j preferentially
• new results from Wise & Abel: feedback from SF & SNe @ z ~ 15 drastically affect the spin distribution of the baryons.

• clearly, a full understanding of angular momentum in galaxies is still in its infancy.

• this understanding is crucial to understand the sizes and shapes of galaxies