L18 - Galaxy Evolution

ELS Collapse Model

Eggen, Lynden-Bell, & Sandage (1962)

A model for the formation of the Milky Way.
ELS observed ~200 dwarf (ie, main-sequence) stars
that had well-characterized Π, Θ, and Z velocities. Close to the Sun now.

Given these velocities, they found eccentricities of the orbits (although they were not closed ellipses) and their specific angular momenta ℓ. Both e and ℓ would be conserved if the ancient galaxy evolved over a time longer than a stellar orbital period.

[Aside: They had photometry for the stars. Metal-poor stars have ~~$E_{U-B} > 0$~~ $\delta(U-B)$ ← [an "UV excess"] *

Observations:

(1) $\delta(U-B)$ increases with e

Metal-poor (older) stars have high eccentricity

handout - Fig 4 of ELS

(2) V_z increases with $\delta(U-B)$

Metal-poor stars have greater V_z, & thus have greater excursions above & below the plane.

handout - Fig 5 of ELS

→ Older stars were formed at any height, while younger ones were born in the disk.

(3) ℓ decreases with $\delta(U-B)$

handout - Fig 6 of ELS

argument for collapse

Metal-poor stars have lower ℓ. ELS: The initial "protogalaxy" could NOT have been in near centrifugal balance. If it had been, the first stars would be in very tight orbits around the center. To get them close to the Sun today, a lot of energy would have to be injected - implausible. So the early cloud was in a state of collapse. Their picture:

- The protogalactic gas cloud began to collapse 10^{10} yr ago. It was rotating.

- As it collapsed stars formed. Today, they are still on near radial orbits, with low ℓ and high e. They constitute globular clusters & metal-poor field stars.

- The collapse of the cloud in R was halted by centrifugal force.
- The " " " " z continued, to form a thin disk.
- With increased density in the disk, star formation increased in rate. Subsequent stars were enriched in metals. They were born into orbits of low-e and high ℓ.

Problems –

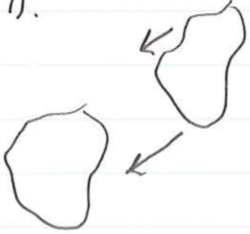
(1) Globular clusters show a range of ages and metallicity. So the "collapse" took several Gyr, not $t_{ff} \sim 10^8$ yr.

(2) Half of halo stars are in retrograde orbits w/ respect to the disk. Hard to explain if the protogalaxy was rotating in one direction initially.

Role of Dark Matter

Galaxies are now seen to form in clumps of dark matter called "halos". These halos formed out of the expanding Universe. They began to separate from the Hubble flow when their ~~[illegible]~~ densities reached ~ 200 × the critical density at that epoch. As we will see $\rho_{crit} \propto H^2$, where H was larger in the past so halos were smaller + denser, with lower masses. Early galaxies also had lower mass.* Milky Way formed "recently" ($z \gtrsim 1$).

evolution of DM halos



Halos were subject to tidal torques, giving them rotation. They also contained a small fraction of ordinary (baryonic) matter, which cooled and fell to the center of the halo, forming a flattened disk. There are (crude) simulations of disk + SF inside disk.

The formation of the stellar halo in the MW + other galaxies is uncertain.

Dimensions of the Disk

It is assumed that both the DM and baryonic matter within the halo follow the NFW profile:

$$\rho(r) = \frac{\rho_0}{\left(\frac{r}{a}\right)\left(1+\frac{r}{a}\right)^2}$$

If R_H is the halo radius, then the "concentration parameter" $C \equiv \frac{R_H}{a}$.
Rotation of the halo is characterized by the "spin parameter" λ,

$J =$ total ang. mom'tm

$$\lambda \equiv J|E|^{1/2}G^{-1}M^{-5/2}$$

where E is the total energy (gravitational + internal kinetic) of the halo

Roughly, let $\rho(r) = \frac{V_c^2}{4\pi G r^2}$ (singular isothermal sphere)

from Mo, Mao, & White 1998

Here V_c is the (eventual) orbit speed in a disk that forms in this halo.
Within the halo,
$$M(r) = \frac{V_c^2 r}{G} \rightarrow \boxed{R_H = \frac{GM}{V_c^2}}$$
If all particles in the halo are on circular orbits, then $\boxed{E = -\frac{MV_c^2}{2}}$

and $$J = \frac{\lambda G M^{5/2}}{|E|^{1/2}} = \frac{\sqrt{2}\lambda G M^2}{V_c}$$

→ Assume that a fraction m_d of M forms the disk, which has a fraction j_d of J.

What is J_d? Let $\Sigma(R) = \Sigma_0 e^{-R/R_d} \rightarrow M_d = 2\pi\int \Sigma R\,dR$
$= 2\pi\Sigma_0 R_d^2$

Then $J_d = 2\pi\int V_c \Sigma R^2\,dR = 4\pi\Sigma_0 V_c R_d^2 = 2M_d R_d V_c$

$$J_d = j_d J$$

$$2M_d R_d V_c = j_d \frac{\sqrt{2}\lambda G M^2}{V_c} \rightarrow R_d = \frac{j_d \lambda}{\sqrt{2} M_d}\frac{GM^2}{V_c^2}$$

But $M_d = m_d M$ $\quad R_d = \frac{1}{\sqrt{2}}\left(\frac{j_d}{m_d}\right)\lambda\frac{GM}{V_c^2}$

But $\frac{GM}{V_c^2} = R_H$ $\quad \boxed{R_d = \frac{1}{\sqrt{2}}\left(\frac{j_d}{m_d}\right)\lambda R_H}$

Simulations give $\lambda \sim \underbrace{j_d \sim m_d}_{} \sim 0.05$ So disk is a factor of ~20 smaller than the halo

reasonable, if baryons have same specific ang. mom. as halo particles

Modeling the Milky Way

If one assumes that the disk has an exponential profile + that the halo follows the NFW profile, one can fit the parameters to observations of the MW, such as the rotation curve, the (baryonic) surface density in our neighborhood, etc.

baryonic compression - distortion of the DM

A subtlety is that, as the disk condenses, dark matter in the halo is also compressed. That is, the inner part of $\rho(r)$ departs from the (assumed) NFW profile. This follows from angular momentum conservation:

The specific ang. mom. in the halo is $\sqrt{\frac{GM}{r}} \times r = \sqrt{GMr}$. Equating this to the specific angular mom. of the same particle in the disk:

$$GM_{halo}(r_i)\, r_i = GM_f(r)\, r$$

$M_{halo}(r_i)$ is the halo mass interior to the initial position r_i. [halo has 64% DM + baryons]
$M_f(r)$ is the final mass interior " " final radius r. This final mass consists of DM interior to r_i plus the amount of disk mass inside r. $\boxed{r < r_i}$
[mass is not conserved because of assumption the disk has exponential profile]

For MW, best-fit values are $R_H = 240$ kpc $\quad M_H = 1 \times 10^{12}\, M_\odot$
$c = 12$ (so $a = 20$ kpc) $\quad$ Klypin et al 2002, ApJ, 573, 597
$\lambda = 0.03$

Problems

In the above model for the MW, only ½ of the baryons in the halo wind up in the disk. The rest may be blown away by SN's, etc, but unknown.

- In detailed simulations, there are too many low-mass halos surviving to the present. We don't see so many dwarf galaxies.
- Disks transfer too much J to DM via dynamical friction, leaving J_d too low
- The formation of the stellar halos + the bulges of the MW and other spiral disk galaxies is poorly understood..

→ The masses of central black holes and the velocity dispersion of bulges is well correlated. This suggests that BH's + bulges formed simultaneously. SF was rapid in the bulge, since dominated by old stars. Evidence for merger.

Morphology – Density Relation

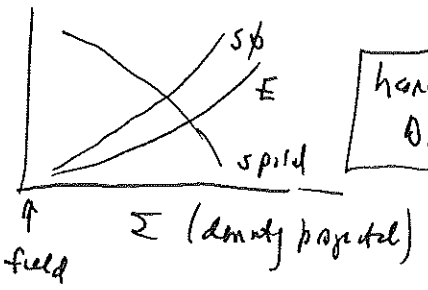
Dressler 1980, ApJ, 236, 351

In the field, ie, away from clusters, the populations of various Hubble types are:

spiral + irregular	80%
S0	10%
ellipticals	10%

Within clusters, one can track these proportions as a function of local density of galaxies.

In the densest regions, spirals become very rare!



handout – Fig 4 of Dressler 1980

Ellipticals are common. Again, they are similar to bulges within spirals.

Galaxies in the Past

In deep, higher-z, surveys, there are many more irregular + "peculiar" galaxies (ones likely to be merging). Moreover galaxies tend to be bluer, indicating higher rates of star formation. Ellipticals are ~~many~~ rarer than today.

Current Ideas

- Initial perturbations created gas clumps of $10^6 - 10^8\ M_\odot$.
- These merged to spheroidal configurations and active star formation: created bulges ~~bulges~~ of today's spiral galaxies + proto-globular clusters.
- Further interactions disrupted others to form halo of old stars + orbiting g. clusters
- Further accretion of lower-density gas led to a disk, in which star formation continues today

Ellipticals – Some are the largest "spheroids" formed early on. Others formed through the merger of pre-existing spiral galaxies.

paradox – Massive halos formed later. So why aren't massive galaxies young? →

NB – The most massive galaxies could have built up recently, through merging of very small ~~galaxies~~ DM halos, which were created at early times. Baryon cooling and SF happened early in these small halos

[Thus, massive galaxies contain the oldest stars]

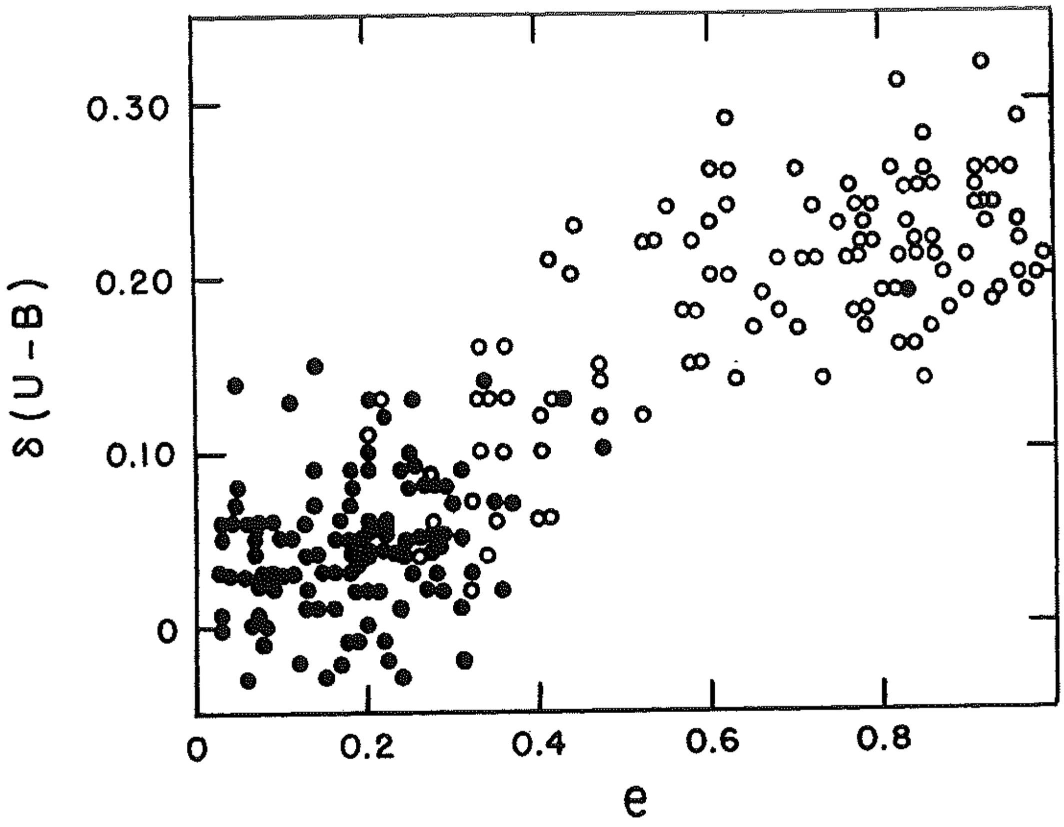


FIG. 4.—The correlation between the ultraviolet excess, $\delta(U - B)$, and the orbital eccentricity, e, for our sample of 221 stars. The filled and open circles represent stars from our first and second catalogues, respectively.

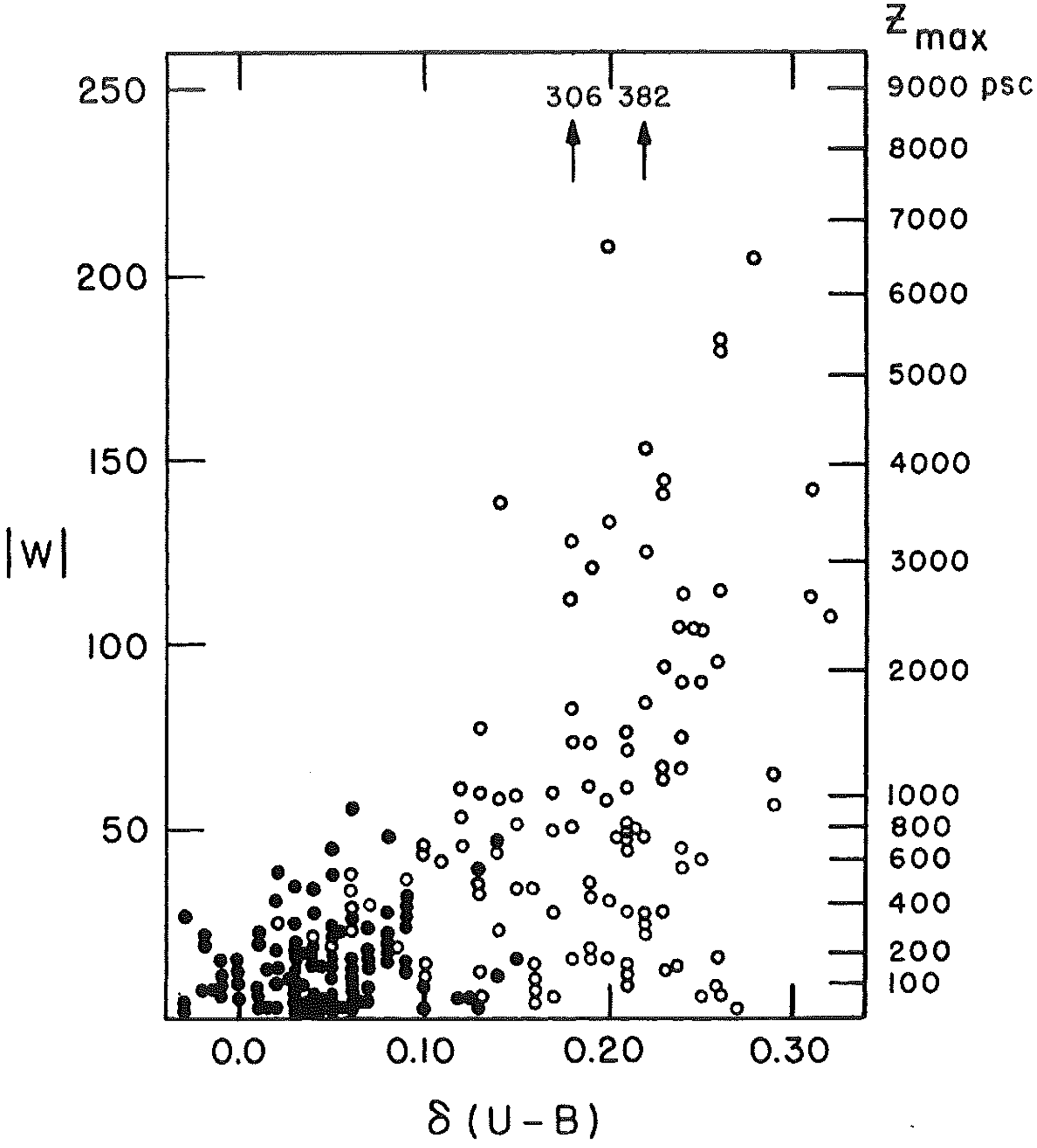


FIG 5 —The correlation between the *W*-velocity, perpendicular to the galactic plane, and the ultraviolet excess for the 221 stars in our sample. The filled and open circles represent the stars in our first and second catalogues, respectively.

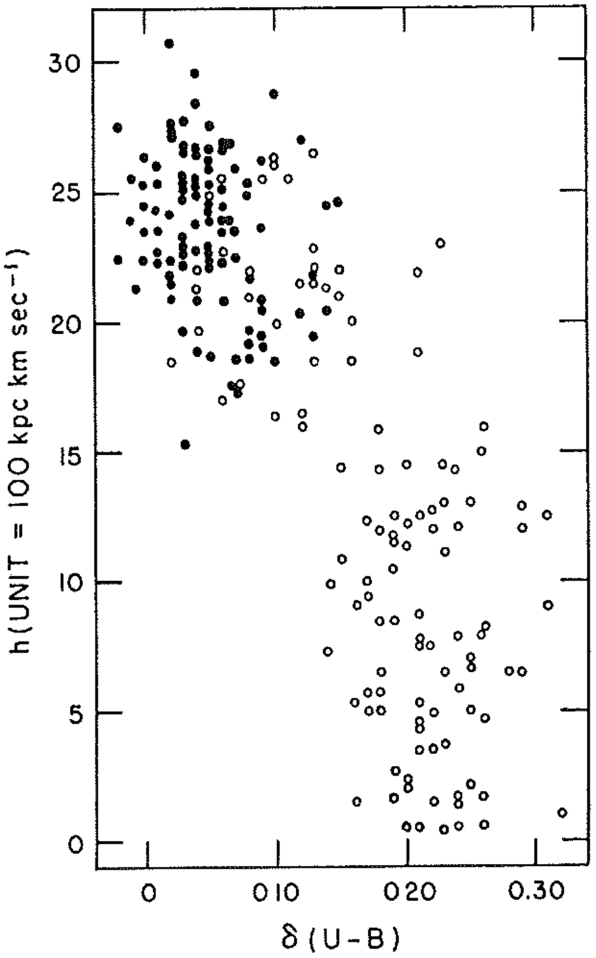


FIG. 6.—The correlation between the angular momentum, *h*, in units of 10^2 kpc km/sec and the ultraviolet excess of the stars shown in Figs. 4 and 5.

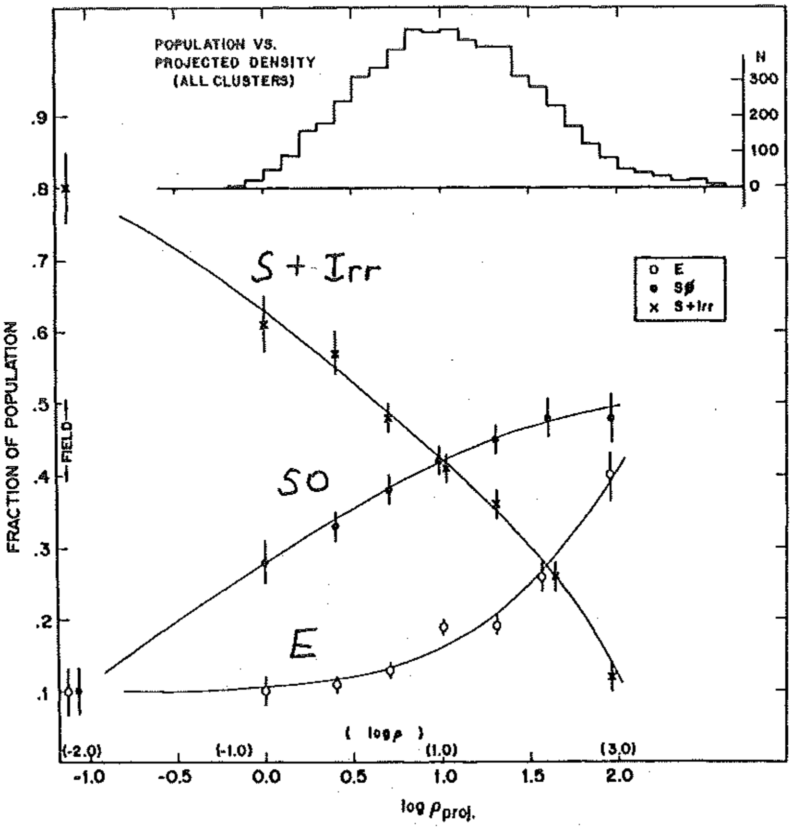


FIG. 4.—The fraction of E, S0, and S+I galaxies as a function of the log of the projected density, in galaxies Mpc^{-2}. The data shown are for all cluster galaxies in the sample and for the field. Also shown is an estimated scale of true space density in galaxies Mpc^{-3}. The upper histogram shows the number distribution of the galaxies over the bins of projected density.