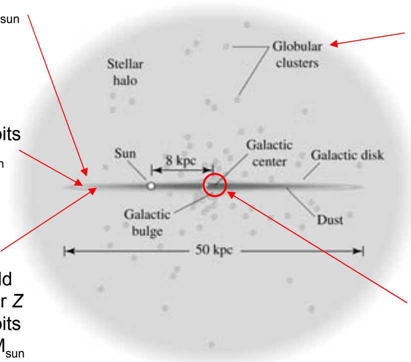
Formation of the Milky Way

Thick Disk
- ~10 Gyr old
- moderately low *Z* (metallicity)
- elongated orbits
- 0.3×10^{10} M_{sun}

Thin Disk
- ~8 Gyr
- solar *Z*
- circular orbits
- 6×10^{10} M_{sun}

Gas Disk
- < 10 Gyr old
- above solar *Z*
- circular orbits
- 0.5×10^{10} M_{sun}



[CO fig 24.6]
+ [CO Tbl 24.1]

Stellar Halo
- 11-13 Gyr old
  - horizontal branch
- very low *Z* (metallicity)
- elongated orbits
- 0.3×10^{10} M_{sun}

Nuclear Bulge
- 0.2 - 10 Gyr old
  - age-flatness correlation
- high *Z* (metallicity)
- elongated orbits
  - but much smaller than for halo stars
- 1×10^{10} M_{sun}

+ dark matter halo
> 230 kpc radius
~ 200×10^{10} M_{sun}

ELS, 1962, ApJ, 136, 748

EVIDENCE FROM THE MOTIONS OF OLD STARS THAT THE GALAXY COLLAPSED

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Received May 17, 1962

VI. SUMMARY

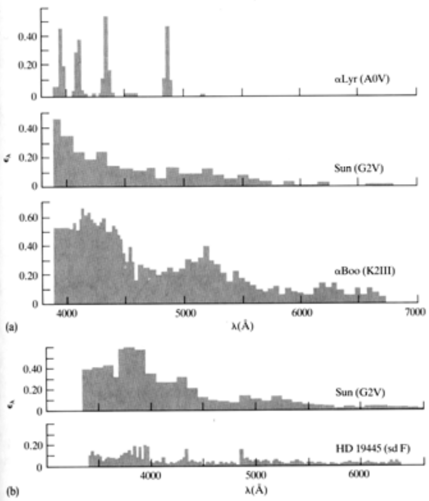
1. Approximately 10^{10} years ago the protogalaxy started to fall together out of intergalactic material. It was either already rotating or acquired its angular momentum from the couples exerted by nearby condensations.

2. As the material fell together, condensations formed which were later to become globular clusters and globular cluster-like stars.

3. The collapse of the galaxy in the radial direction was eventually stopped by rotation, but that in the *Z*-direction continued, giving rise to a thin disk. With the increased density, the rate of star formation increased. In their evolution the first-generation stars enriched the remaining gas with heavy elements formed in their interiors, with the result that later generations, formed from this same material, show smaller ultraviolet excesses.

4. The gas, which must have become hot, radiated away much of the energy of collapse. At first, the gas followed the orbits of the stars that were formed from it, but the gas and the stars became separated near perigalacticum, after which, relieved of its extra energy by collisions with other gas clouds, the gas settled into circular orbits appropriate to its angular momentum and continued to produce later generations of stars that also move in nearly circular orbits. The first-generation stars, on the other hand, continue in the highly eccentric orbits produced by the original collapse.

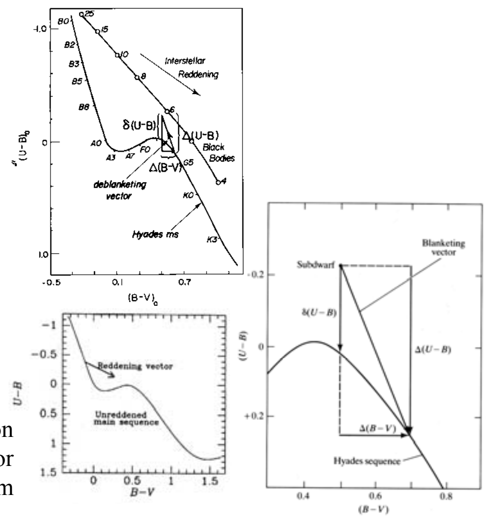
Measuring metallicity from colors



Line blocking as a function of λ

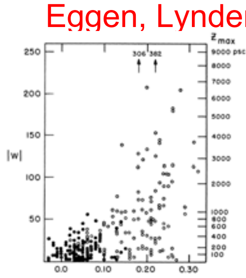
For main-sequence stars:

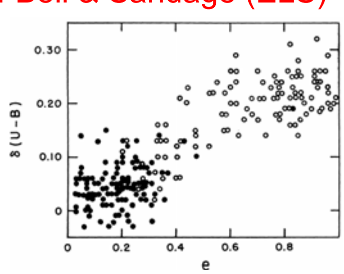
- More metals ➔ higher absorption coefficient.
- Line-blanketing *vs.* back-warming.

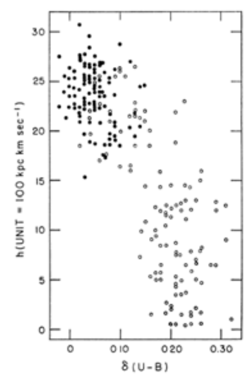


Effect on color-color diagram

Eggen, Lynden-Bell & Sandage (ELS)







Orbits of 221 stars selected by *high velocities* relative to Sun.

δ(U-B) ➔ metallicity; δ(U-B) ~ 0 ➔ solar metallicity; δ(U-B) large ➔ metal poor.

Angular Momentum vs. δ(U-B)

- Rule out star formation before collapse
  - If gas cloud self-supporting on galaxy-sized scale, also self-supporting on star-sized scale.
- Ang. Momentum of metal-poor stars same as for stars in circular orbits at R ~ 5 kpc, but halo stars have much higher energy orbits

  ➔ galaxy not in dynamical equilibrium when halo stars formed.

  ➔ halo stars formed from infalling gas.

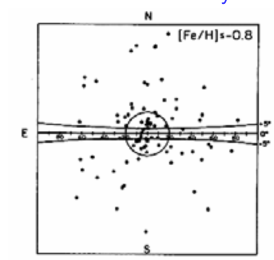
Timescale & extent of collapse:

- Large observed *e* ➔ collapse faster than rotation period of ~10^8 yrs. ➔ all halo GCs formed within 10^8 yrs
- Collapse in Z direction is factor ~25
  - From max Z of halo stars vs. thickness of gas disk
- Collapse in R direction is factor ~ 10
  - Angular momentum of individual gas elements stays constant as gas goes from collapse to disk.
  - ➔ compare R_{max} of halo stars to R of disk stars with same angular momentum.

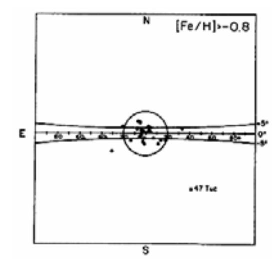
Problems for ELS Model

- Halo stars have angular momentum ~ 0
  - ~ ½ of all halo stars are in retrograde orbits
- Globular cluster age spread
  - 3 billion yr spread not consistent with freefall timescale t_{ff} ~ 6x10^8 yrs.
- Range of globular cluster chemical abundances
  - Near galactic center ➔ metal rich, but (perhaps) older.
  - Outer halo ➔ wider range in [Fe/H], but on average younger.
  - Spheroid vs old disk G.C. distributions:
- Multi-component disk with different ages.
- Evolution of chemical abundances
  - G dwarf problem

Globular Cluster Distribution on sky

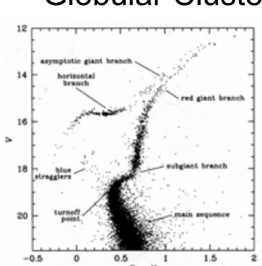


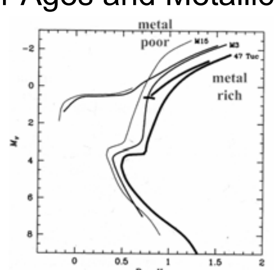
Metal poor

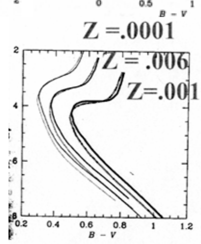


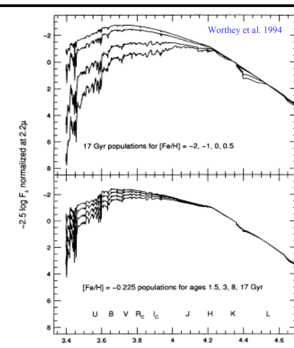
Metal rich

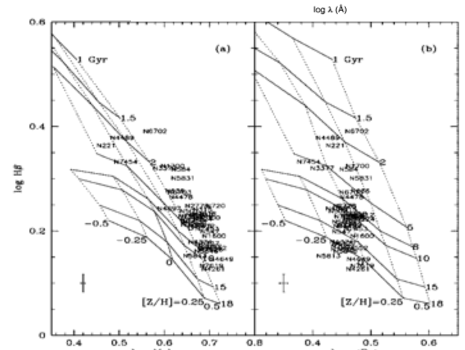
Globular Cluster Ages and Metallicities











Trager et al. 2000

Age-metallicity degeneracy in fits

- Must use several indices.
- Easy to confuse age effect with metallicity effect.
- Hard to get absolute calibration of metallicity.

Closed Box Models

(and friends and relatives)

Metallicity
$Z = M/G$
$Z_\odot \sim 0.02$

Gas ➔ stars ➔ enriched gas

S = mass of stars

M = mass of metals (heavy elements) in ISM

G = total mass of gas in ISM

Assume instantaneous recycling from massive stars.

From a new generation of stars:

dS = mass of low mass stars added to S

$p\,dS$ = mass of heavy elements added to M from massive stars in this generation. where p = *yield*.

$$dM = p\,dS - Z\,dS$$
$$= -p\,dG + Z\,dG \qquad \text{since } dG = -dS$$

But $$dZ = d(M/G) = (1/G)\,dM - (M/G^2)\,dG$$
$$= -p\,(dG/G)$$

$$Z(t) = -p \ln [G(t)/G(0)] \quad \text{or} \quad G(t) = G(0)\,e^{-Z(t)/p}$$

Also… Leaky box (gas driven out by stars), Accreting box models.

G dwarf problem

$$S[Z<Z(t)] = S(t) = G(0) - G(t)$$
$$= G(0)\,\{1 - e^{-Z(t)/p}\}$$

$Z(t)$ = gas metallicity at time t

Compare to case when gas had some arbitrary fraction α of that metallicity:

$$\frac{S[Z<\alpha Z(t)]}{S[Z<Z(t)]} = \frac{1-X^{\alpha}}{1-X}$$

where $X = \dfrac{G(t)}{G(0)} \sim 0.1 - 0.2$

Predicts broad distribution in metallicity of stars.

➔ $S[Z<1/4\,Z_\odot] = 0.4\,S[Z<Z_\odot]$

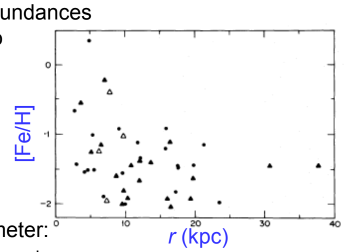
Very different than what is observed in solar neighborhood:

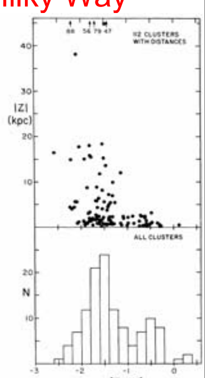
$S[Z<1/4\,Z_\odot] = 0.02\,S[Z<Z_\odot]$

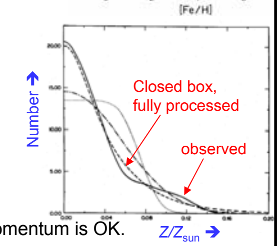
Bottom-up (Hierarchical Merger) Formation of Milky Way

Searle & Zinn (1978)

- Motivated by large range in metal abundances of halo globular clusters in outer halo
  - No radial abundance gradient
    - ➔ Not slow contraction
  - Consistent with either
    - formation during freefall
      - » ELBS model
    - or mergers.
- Claim that *age* is an additional parameter:
  - Tightly bound clusters – small age spread
    - inner halo collapsed in < 10^9 yrs
  - Loosely bound clusters – large age spread
    - Outer halo $t_{collapse}$ > 10^9 yrs.
- Distribution of [Fe/H] ➔ all gas used up
  - (if a closed box model)
  - No gas left over for later formation of disk
  - Alternate explanation: many stripped subsystems
- MW assembled from ~ $10^8\,M_{sun}$ "proto-galactic fragments" which had already formed stars and undergone chemical evolution.
  - Halo formed from different fragments than disk, so different angular momentum is OK.
  - Dense central region evolved rapidly ➔ high [Fe/H] bulge of today
  - *Halo formed from inside to outside* (bulge formed first).



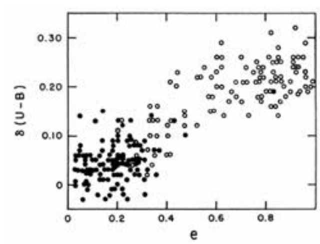




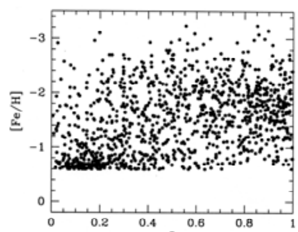
See also Zinn 1980, 1985

Embellishments to Bottom-Up Model

- Thick disk
  - formed during slow dissipative collapse of remaining gas, which had angular momentum
    - Heating, metal enrichment through SNe over ~400 million yrs.
    - T ~ 10^6 K ➔ scale height ~ 1.6 kpc
- Collapse to old thin disk
  - Star formation in thin disk over next 5 billion yrs
  - Further gradual collapse to thinner gas disk we see today.
- Metallicity vs. orbital eccentricity of halo stars



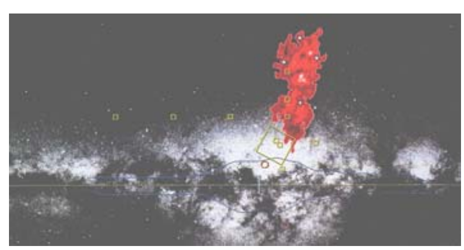
data used by ELBS (1962)

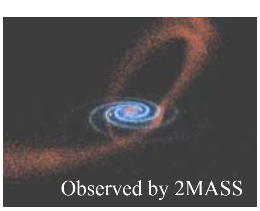


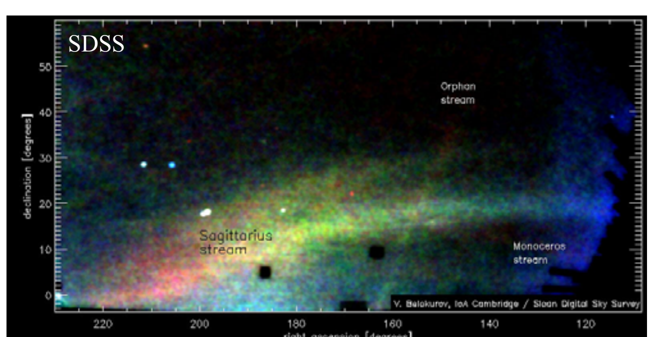
Tim Beers' bulletin board (2000)

Milky Way Mergers

- Recent/current dwarf galaxy mergers
  - Sagittarius
  - Monoceros
  - Canis-Majoris
- Show up as star streams in halo
- Magellanic clouds
  - Magellanic stream (H I gas)
  - But recent result casts doubt







MW Formation: Bottom-Up or Top-Down?

- Favoring bottom-up
  - ΛCDM cosmology says so!
  - Small galaxies currently merging with MW
  - Halo has two major components
    - Distinct metallicities and kinematics (Carrollo, Beers et al. 2007)

- Favoring top-down
  - Disk clearly formed from gas, not from stars pre-formed in smaller sub-units.
  - ΛCDM predicts 100s of low mass DM halos still orbiting MW
    - Only 10-15 are seen.
    - But SDSS is starting to find more

- Top-down apologia
  - Thick disk may be stars stirred up from thin disk by accretion of dwarf galaxies.
  - Bulge stars may be formed from gas falling in from halo and disk.

The issue is still unclear…
May be a combination of both, or bottom-up may do it all.