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GC FORMATION IN MERGERS: OBSERVATIONS

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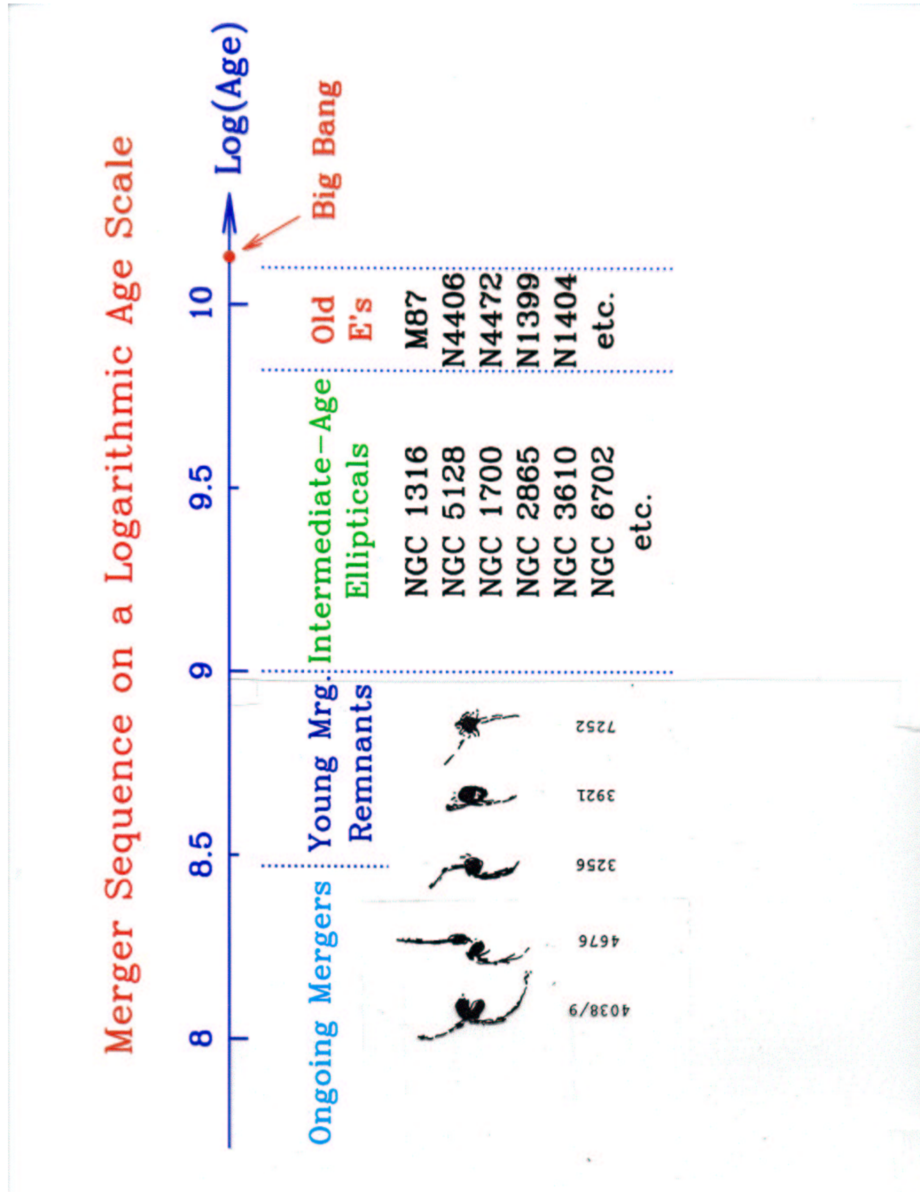
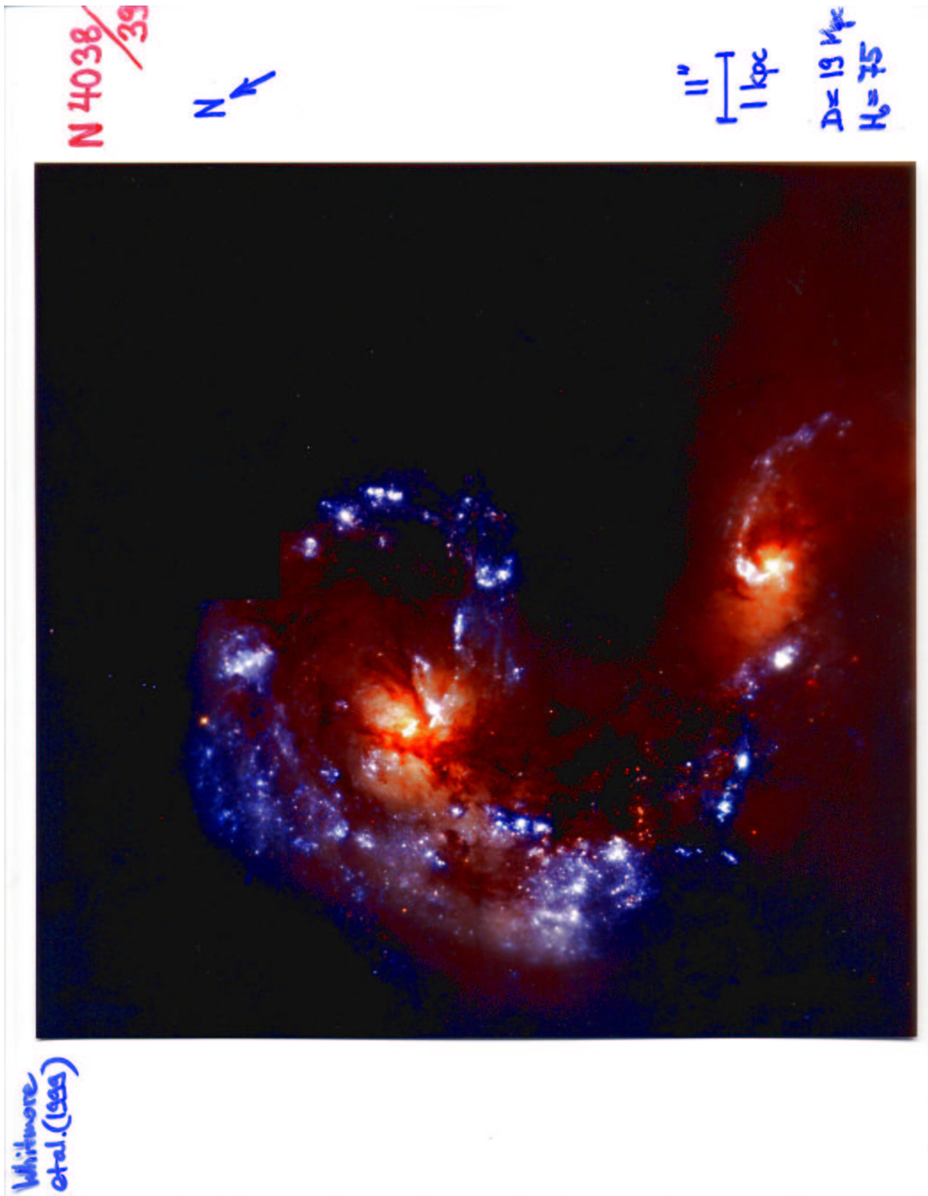
1. Nature of Young Clusters
2. Formation & Early Evolution ($\lesssim 10^8$ yr)
3. Reaching Adulthood ($10^8 - 10^9$ yr)
4. Systemic Evolution (10^{10} yr)
5. Implications

Collaborators:
HST: B. Whitmore, M. Fall, B. Miller, A. Kundu
Spectroscopy: P. Seitzer, J. Brodie, J. Strader

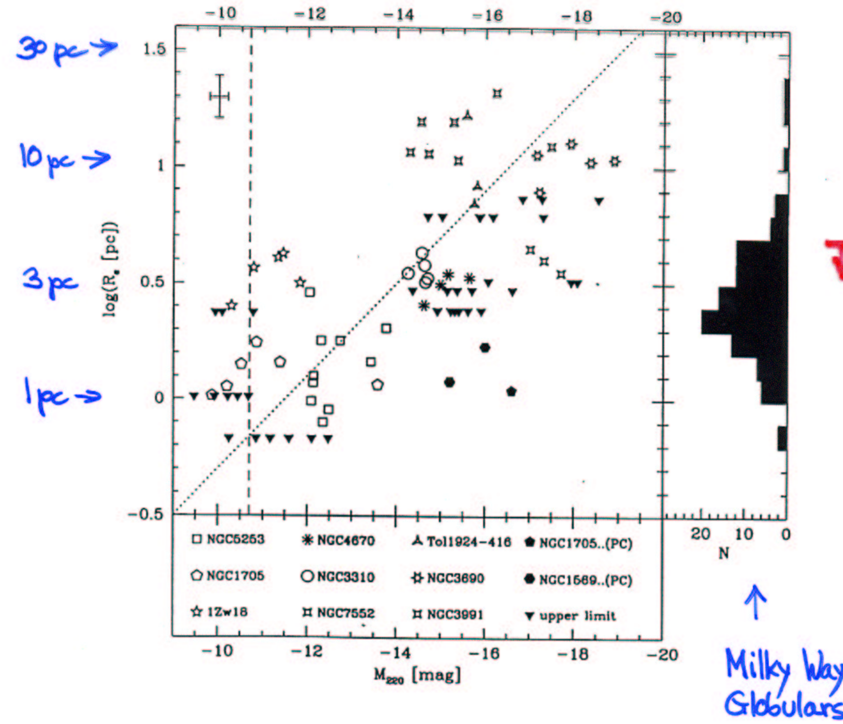
Support: NSF (AST); NASA (StScI); Carnegie





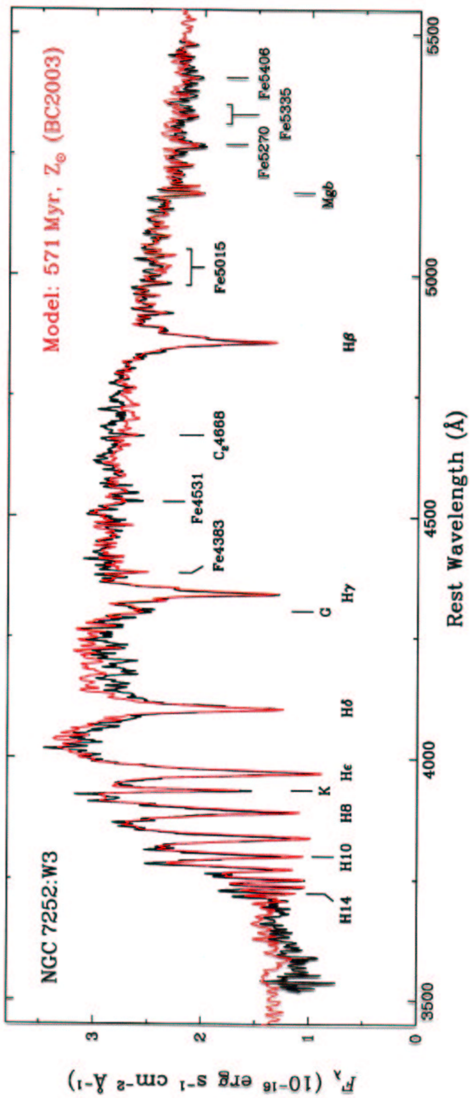
Meurer et al. (1995), HST-3/FOC

Effective Radii of Candidate Clusters in UV



→ The effective radii of luminous clusters formed in starbursts are typical of Milky Way globular clusters

Spectrum of Cluster W 3 in NGC 7252



- Best fit for Age $\approx 530 \pm 40$ Myr $\approx 10^2\ t_{\rm cross}$ (core-crossing times)
- $\Rightarrow$ Gravitationally bound; $R_{\rm eff} \leq 7$ pc $\Rightarrow$ Globular Cluster

Masses of Young Clusters

Photometric masses, based on cluster-evolution models (e.g., Bruzual & Charlot 1996, 2003) and measured luminosities and ages:

typically: $M_{\rm phot} \approx 10^3 - 10^7\ M_\odot$

Main assumption: Stellar IMF within cluster (e.g., Salpeter 1955, Kroupa 2001, Chabrier 2003).

Extreme mass: NGC 7252:W3

$M_{\rm phot} = 1.8 \times 10^8\ M_\odot$ Schweizer & Seitzer 1998

$7 \times 10^7\ M_\odot$ Maraston et al. 2001

Dynamical masses: $M_{\rm dyn} = 3\,\sigma_v^2\,R_{\rm eff}/G \quad (R_{\rm eff} \approx R_{\rm h})$

typically: $M_{\rm dyn} \approx 10^4 - 10^{6.7}\ M_\odot$

densities: $\rho \approx 10^4 - 10^5\ M_\odot/{\rm pc}^3$

Examples:

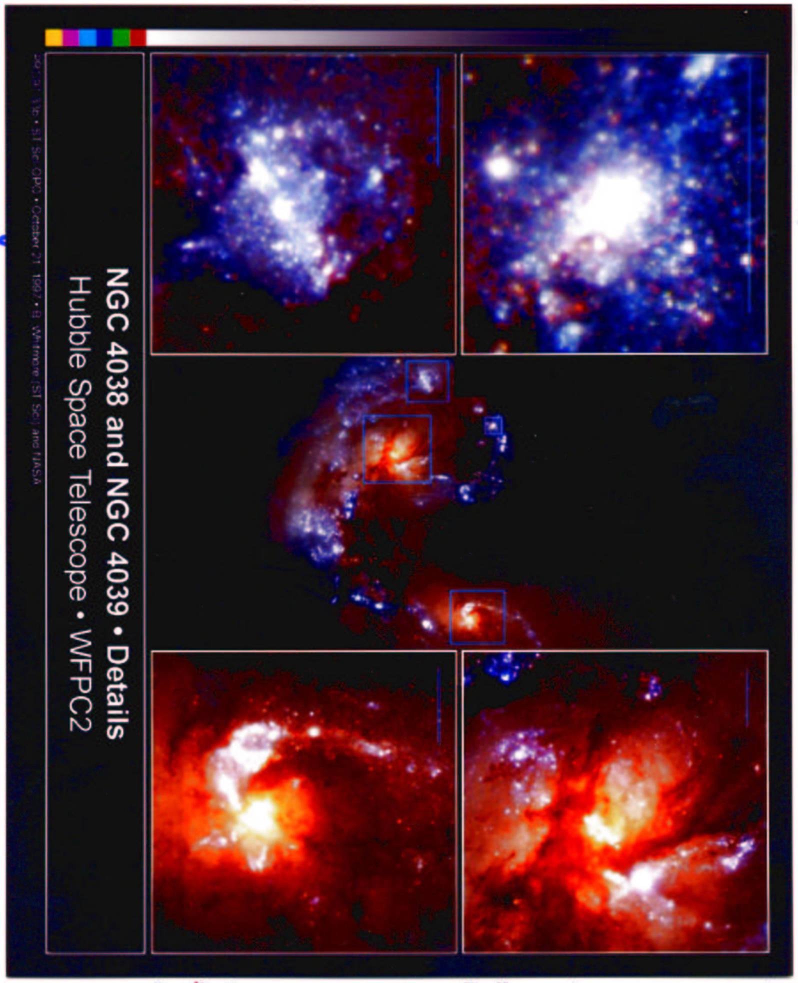
- N1569, 1705: $3 \times 10^5, 8 \times 10^4\ M_\odot$ — Ho & Filippenko 1996
- N4038/39: $6 \times 10^5 - 5 \times 10^6\ M_\odot$ — Mengel et al. 2002
- M82: $1.2 \times 10^6\ M_\odot$ — Smith & Gallagher 2001

Knots identified by Rubin, Ford, & D'Odorico (1970)

"G" "S"

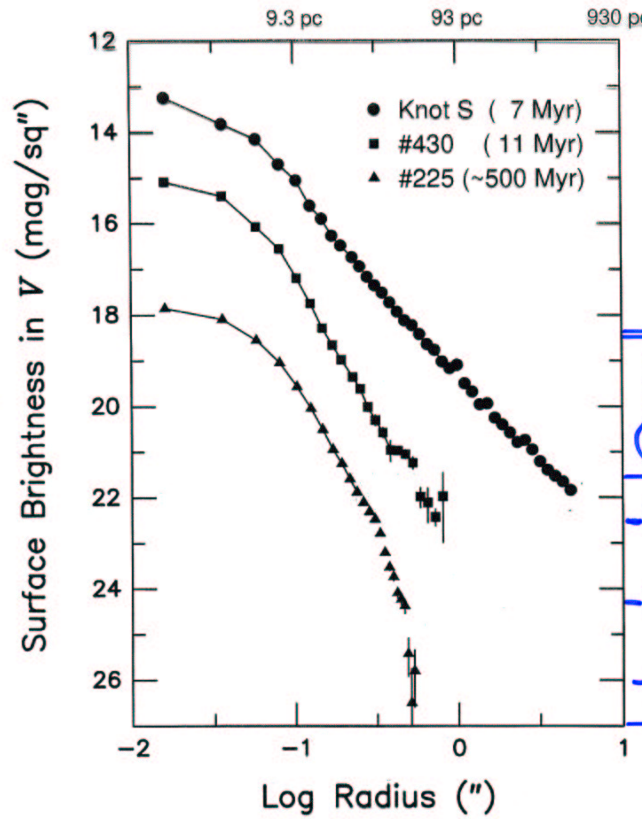
13."6 ≈ 1.2 kpc

5."78 ≈ 530 pc



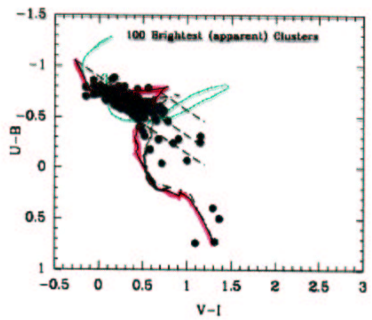
"A" (nucleus of '39) "J" + "K" (nucleus of '38)

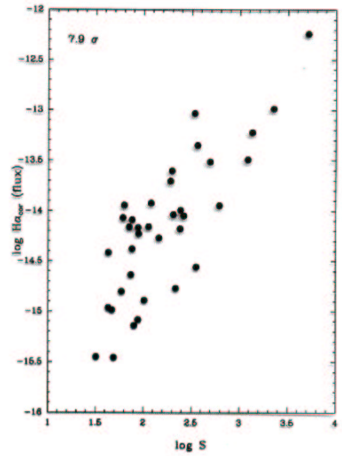
Radial Brightness Profiles of 3 YGC in NGC 4038



M_V (mag)	r_c (pc)	R_t (pc)
−15.8	<4.2	>450
−13.1	<4.6	>75
−9.9	5.6	50

Power laws: Knot S $\gamma = -1.6 \pm 0.1$
#430 -2.7 ± 0.2

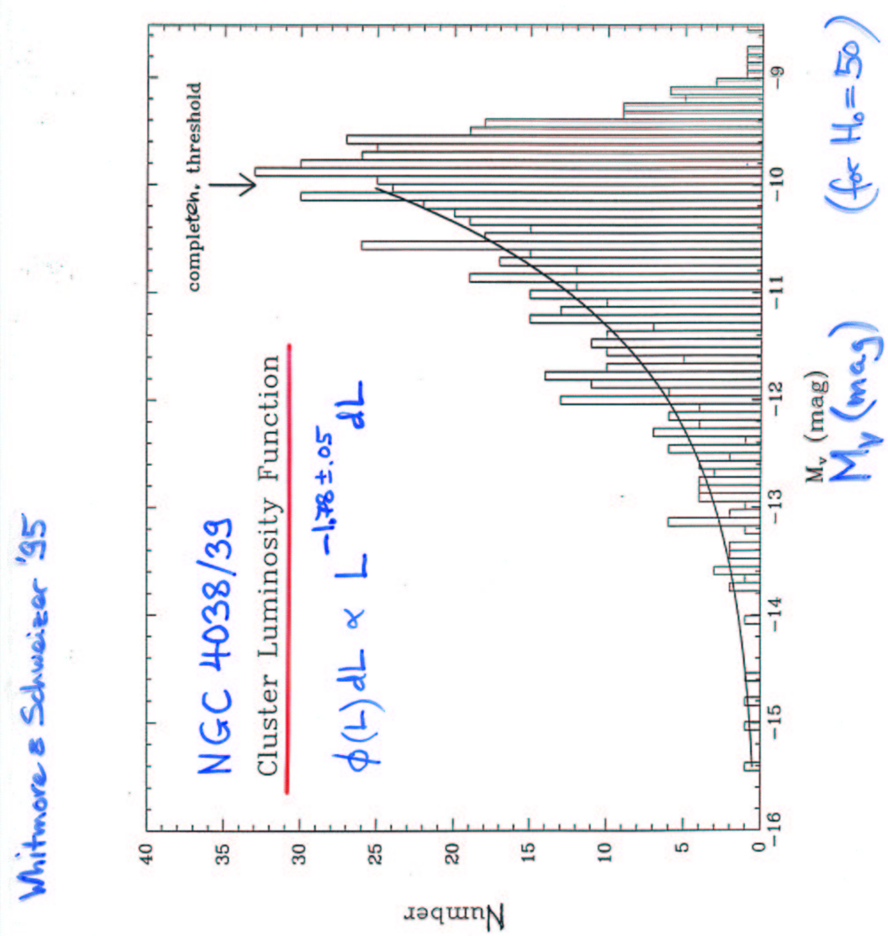




Young Clusters: Extinctions & Radio Emission

(Whitmore & Zhang 2002)

- Claims of extreme extinctions ($A_V > 50$ mag) & many missing clusters in Overlap Region of N4038/39 appear incorrect: Fully 85% of all strong thermal radio sources have optical counterparts. Cluster extinctions are $A_V = 0.5 - 7.6$ mag and diminish to $A_V < 1.0$ mag after ~6 Myr.
- Cluster WS80 (Whitmore & Schweizer 1995) is both the brightest radio source and intrinsically brightest optical cluster ($M_V = -15.5$); it is ~2 Myr old.
- After correction for extinction, the Hα flux correlates with the radio emission.
- Cluster locations in $(U - B,\ V - I)$ diagram favor evolutionary tracks of new Bruzual–Charlot (2003) models over those of Starburst99 (Leitherer et al. 1999) models.



Giant Molecular Clouds As GC Progenitors

1. Luminosity functions of young clusters and mass functions of GMCs are similar

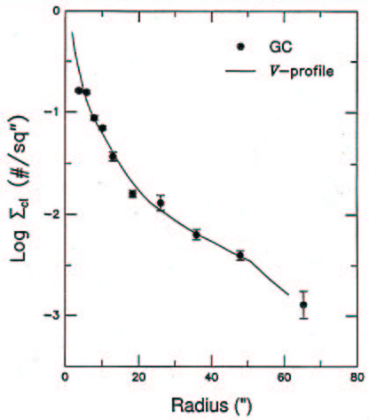
$$N(\mathrm{GC}) \propto L^{-1.6 \text{ to } -2}$$
$$N(\mathrm{GMC}) \propto M^{-1.6}$$

2. Mass ranges of globulars and GMCs are similar

GC: $\sim 10^5$–$5\times10^6\ M_\odot$

GMC: $\sim 10^5$–$8\times10^6\ M_\odot$

3. Young GCs and/or progenitors experienced the same violent relaxation as did the average luminous matter ⇒ Progenitors were compact

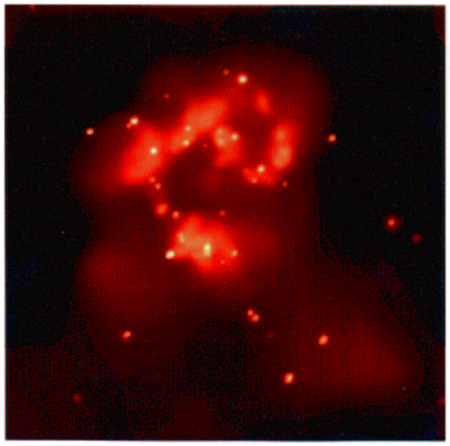


Radial profile of GC distribution and V-light in NGC 3921

Only candidate progenitors in spirals: GMCs squeezed by overpressure (Jog & Solomon 92)

Cluster Winds & 'Superbubbles'

NGC 4038/39 (Fabbiano, Zesas, & Murray 2001):



Typical Superbubble:

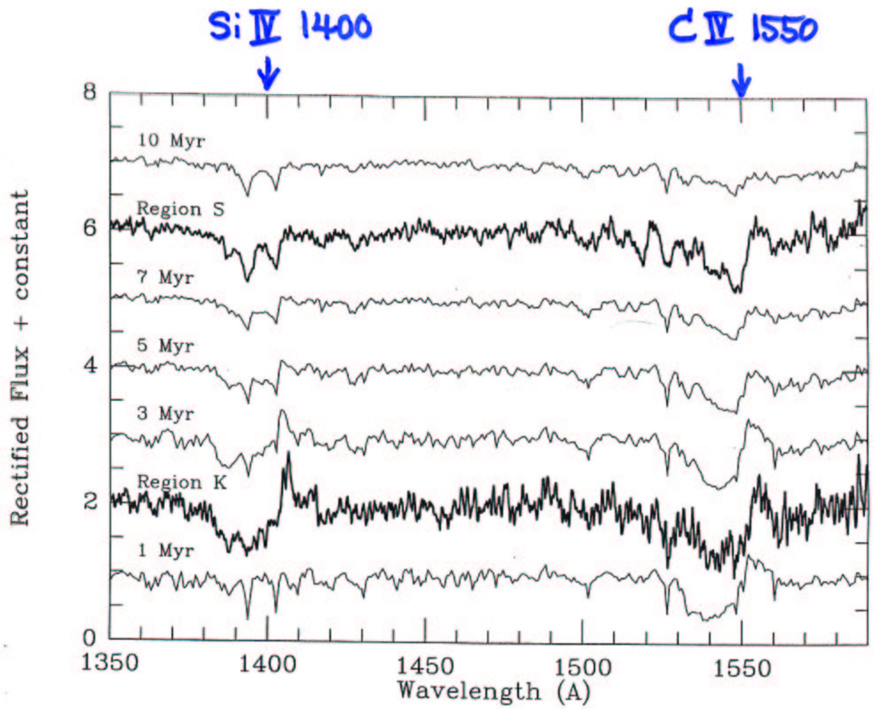
- X-ray emission rimmed by Hα shell, diameter $\sim$1.5 kpc
- Optically-thin-plasma spectrum, $T \approx 5\times10^6$ K (adopted)
- Lumin: $L_X \approx 10^{39-40}$ erg/s $\approx$ 10 – 100 L_X (30 Dor, M101 sbbl)
- Mass in X-ray gas: $M_X \approx 10^{5-6}\ M_\odot$

Typical Cluster Wind (Models by Stevens & Hartwell 2003):

- Cluster wind = sum of individual stellar winds
- Flow time within cluster: $\tau_{\rm cl} \approx 10^{3-4}$ yr
- Superbubble time scale: $\tau_{\rm sbbl} \approx$ cluster age $\approx 10^{6-7}$ yr
- $T_{\rm central} \approx 10^{7-8}$ K, $V_{\rm term} \approx 2000$ km/s, mass loss rate $\approx 10^{-4} M_\odot$/yr

Whitmore,..., Leitherer,... et al (1999)

UV Spectra of Knots S and K in NGC 4038

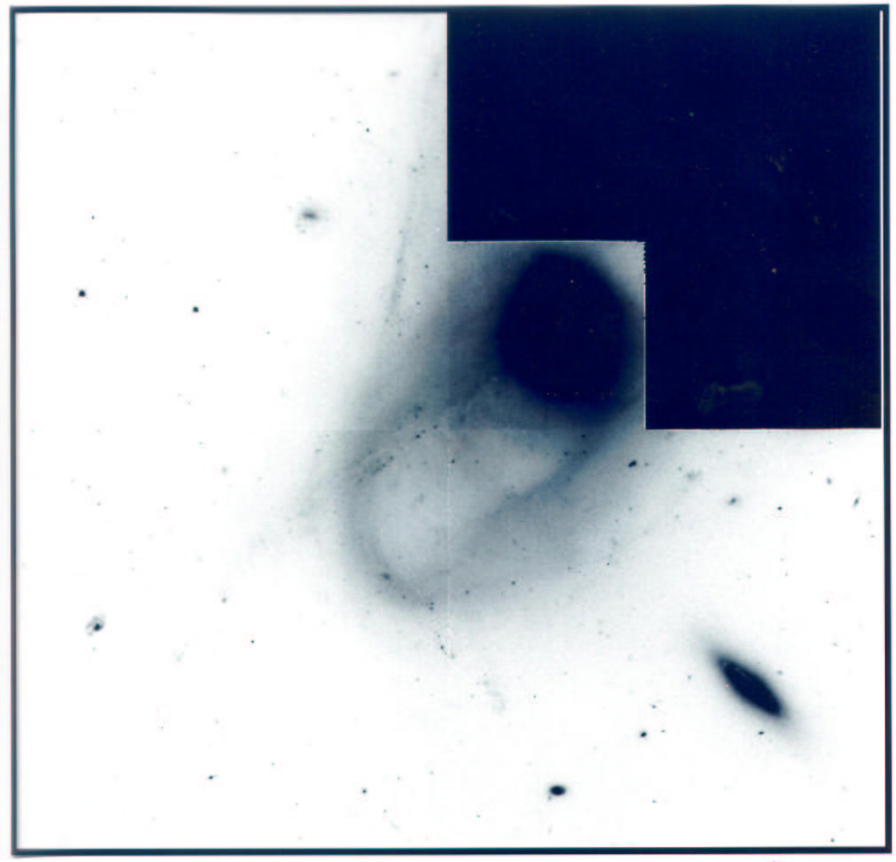


Aperture 1."7 × 1."7 ; Models: Salpeter IMF, ~$Z_\odot$ (Leitherer et al. 1999)

→ Age (Knot S) = 7 ± 1 Myr
" (" K) = 3 ± 1 "

Each Knot has $L_{1500} = 4.4 \times 10^{38}$ erg s^{-1} $Å^{-1}$

Young GC's + Associations in NGC 3921

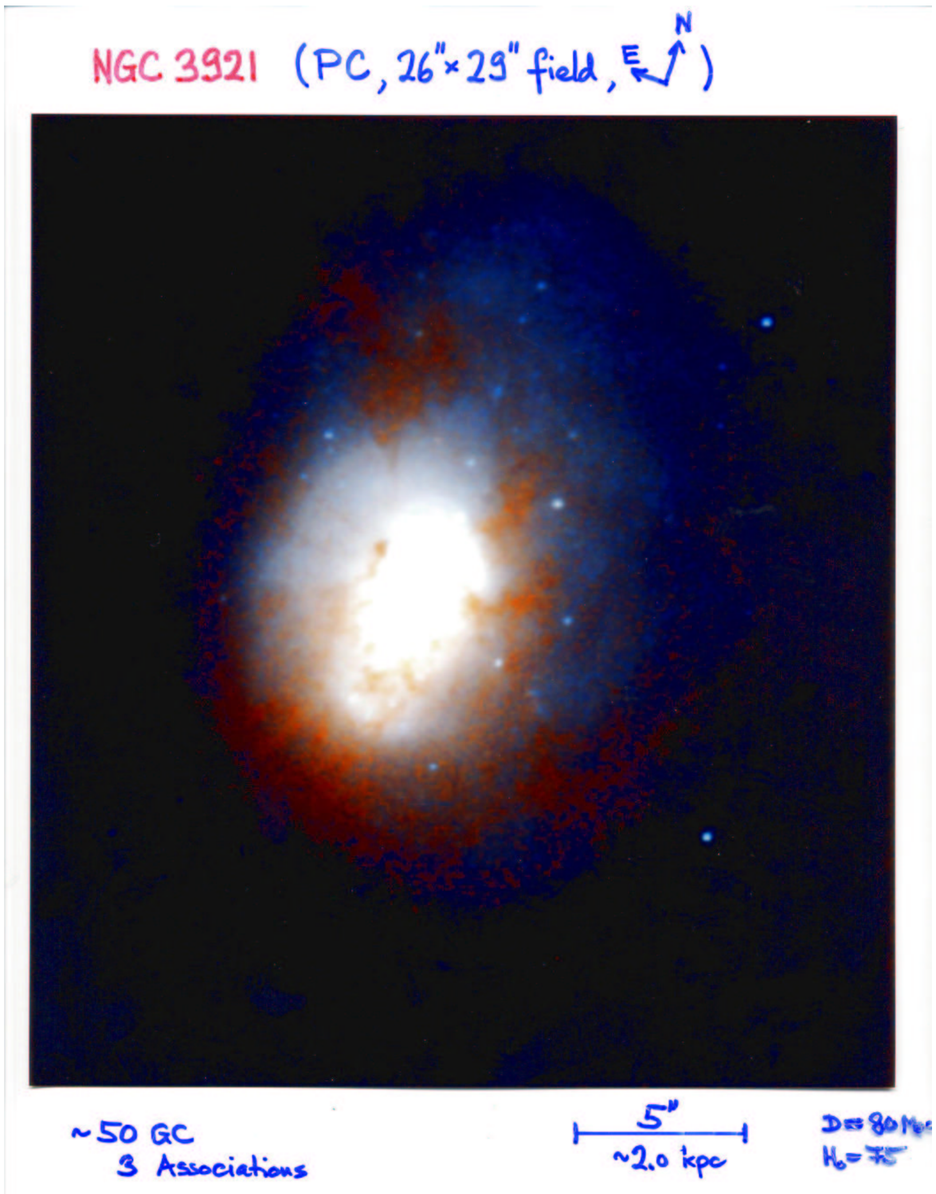


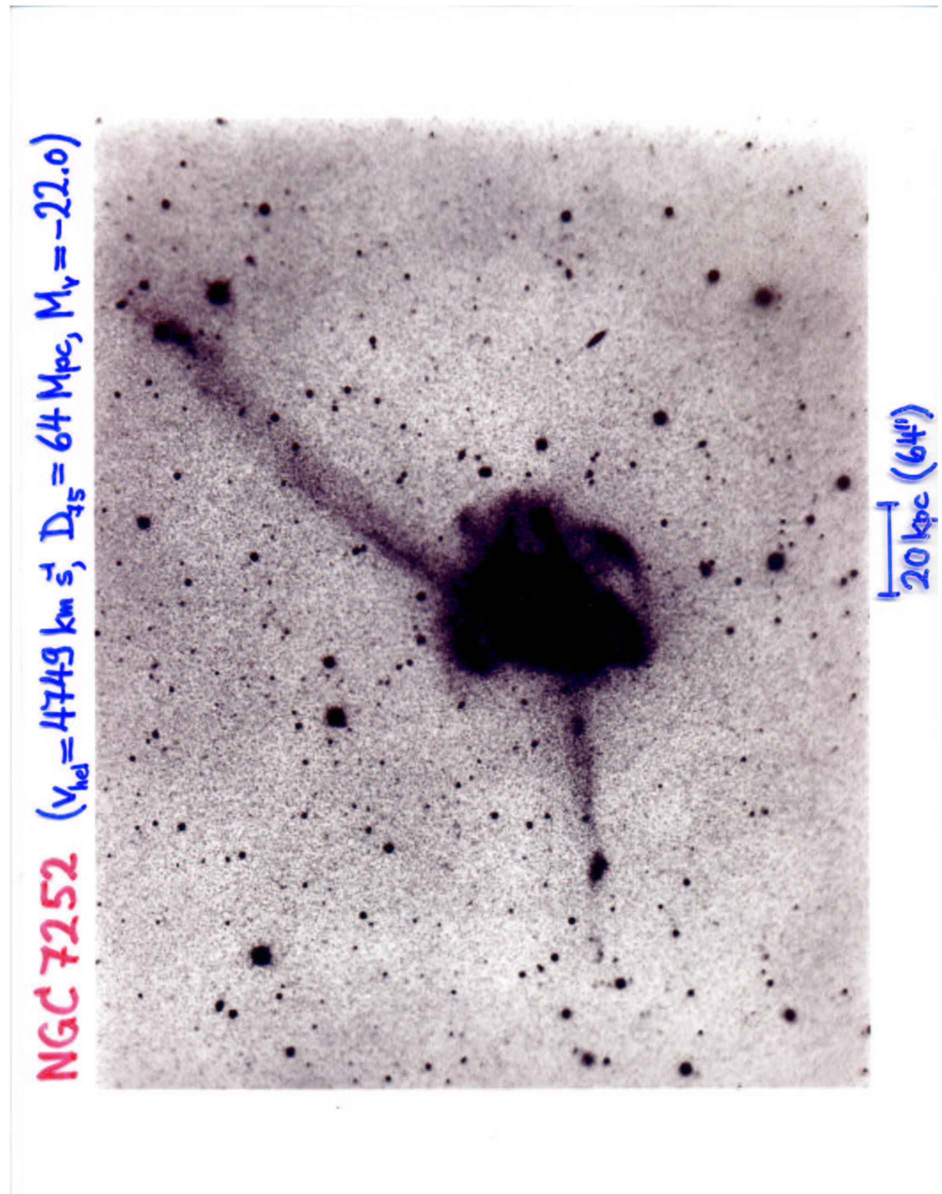
N

25."7
10 kpc

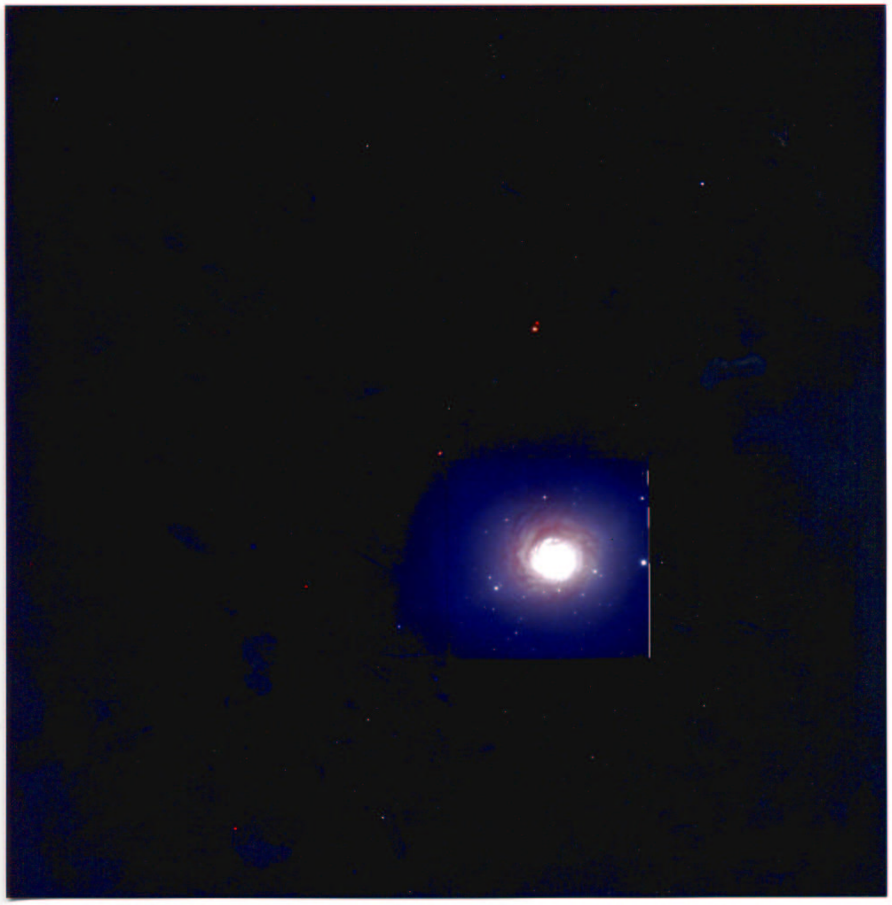
102 GC
+ 49 separate Associations ("Faint Fuzzies"?)

D = 80 Mpc, $H_0 = 75$


NGC 3921 (PC, 26"×29" field, E N)
~50 GC
3 Associations
5"
~2.0 kpc
D=80 Mpc
H0=75


NGC 7252 (V_hel = 4749 km s^-1, D_75 = 64 Mpc, M_V = -22.0)
20 kpc (64")

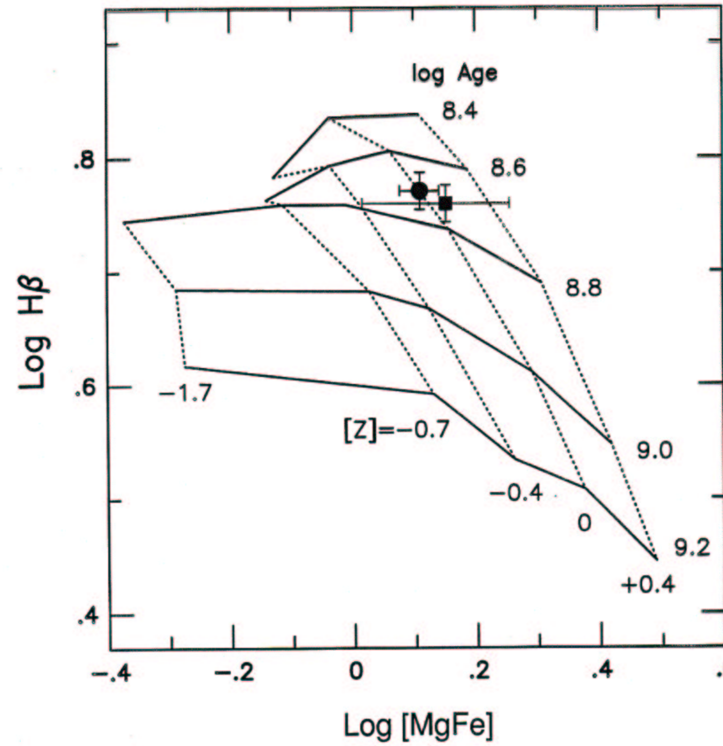
NGC 7252 (HST-4, Miller et al. 1997)



~500 candidate clusters V ≤ 26 mag

32″ — 10 kpc

Age–Metallicity Diagram for 2 Young Globulars in NGC 7252

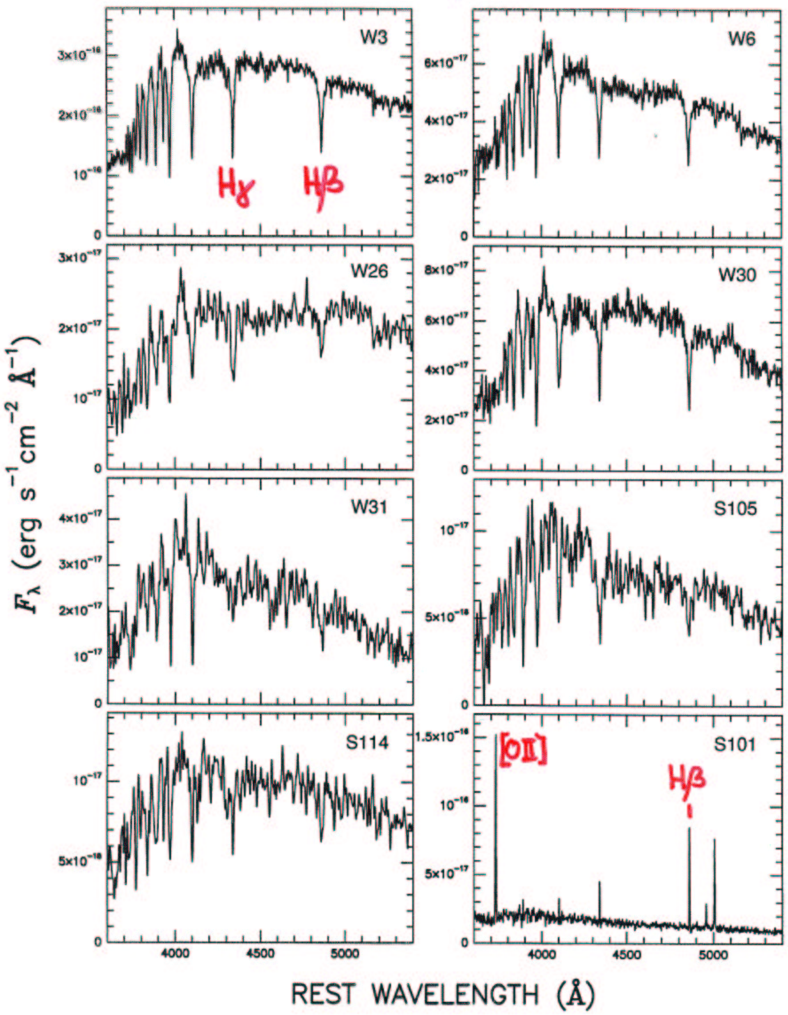


W3
W6

(based on cluster models by Bressan et al 1996)

→ W3: Age = 500 ± 20 Myr, [Z] = 0.00 ± 0.08
W6: 520 ± 30, +0.10 ± 0.17
[+ emission-line S101: ≤10 Myr, −0.12 ± 0.04]

Spectra of 8 Clusters in N7252
(Schweizer & Seitzer 1998)



MILLER *ET AL.*: STAR CLUSTERS OF NGC 7252 (1997)

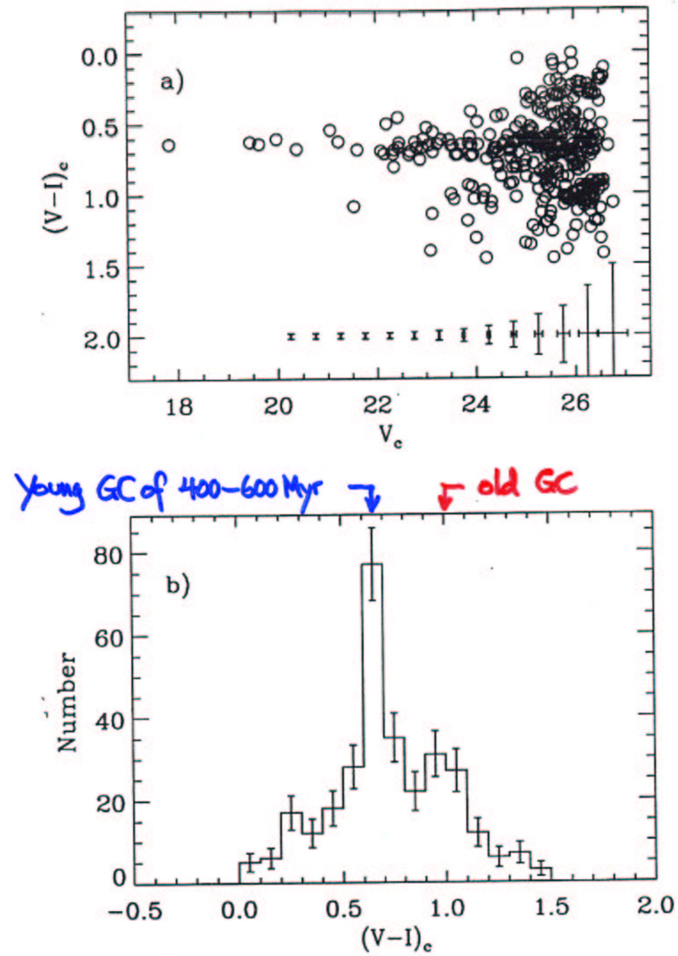
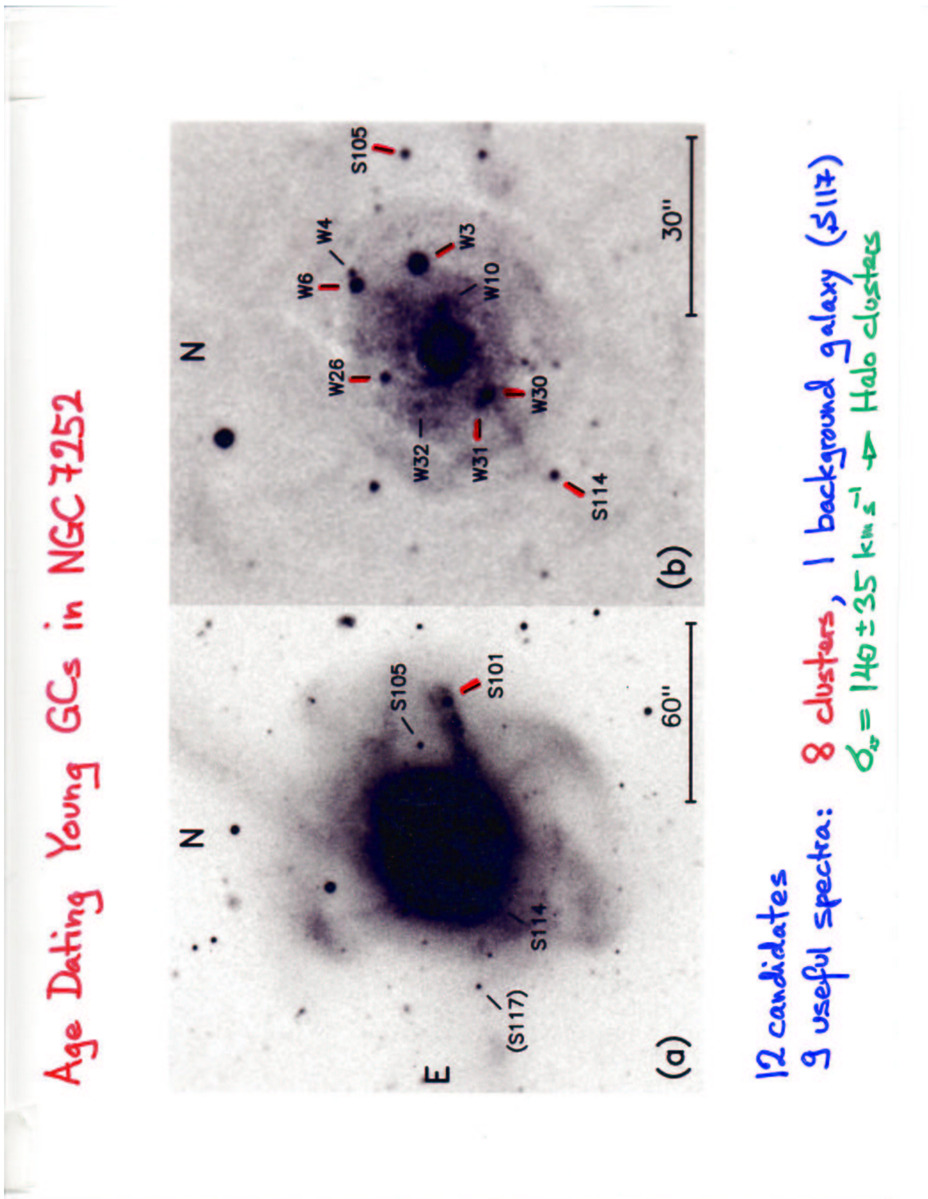
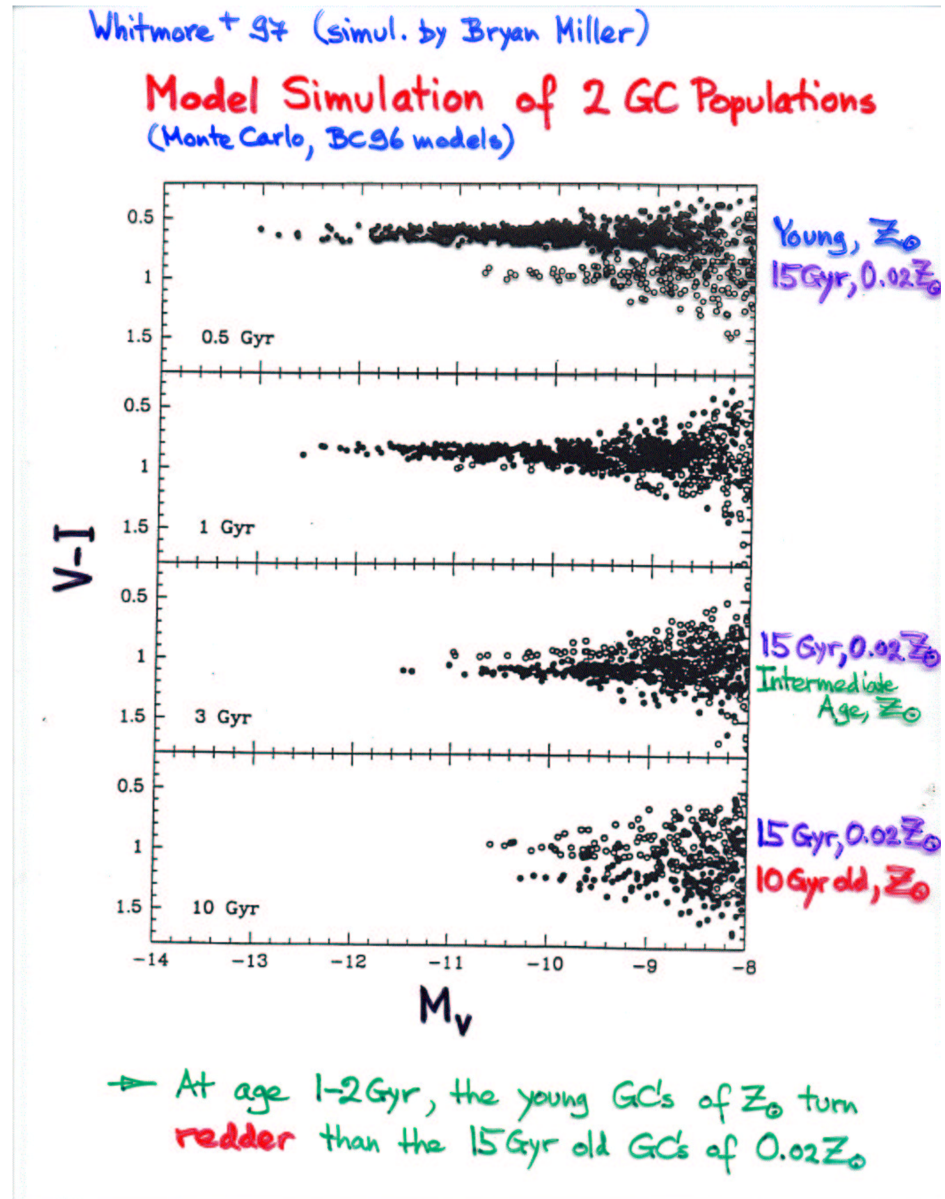
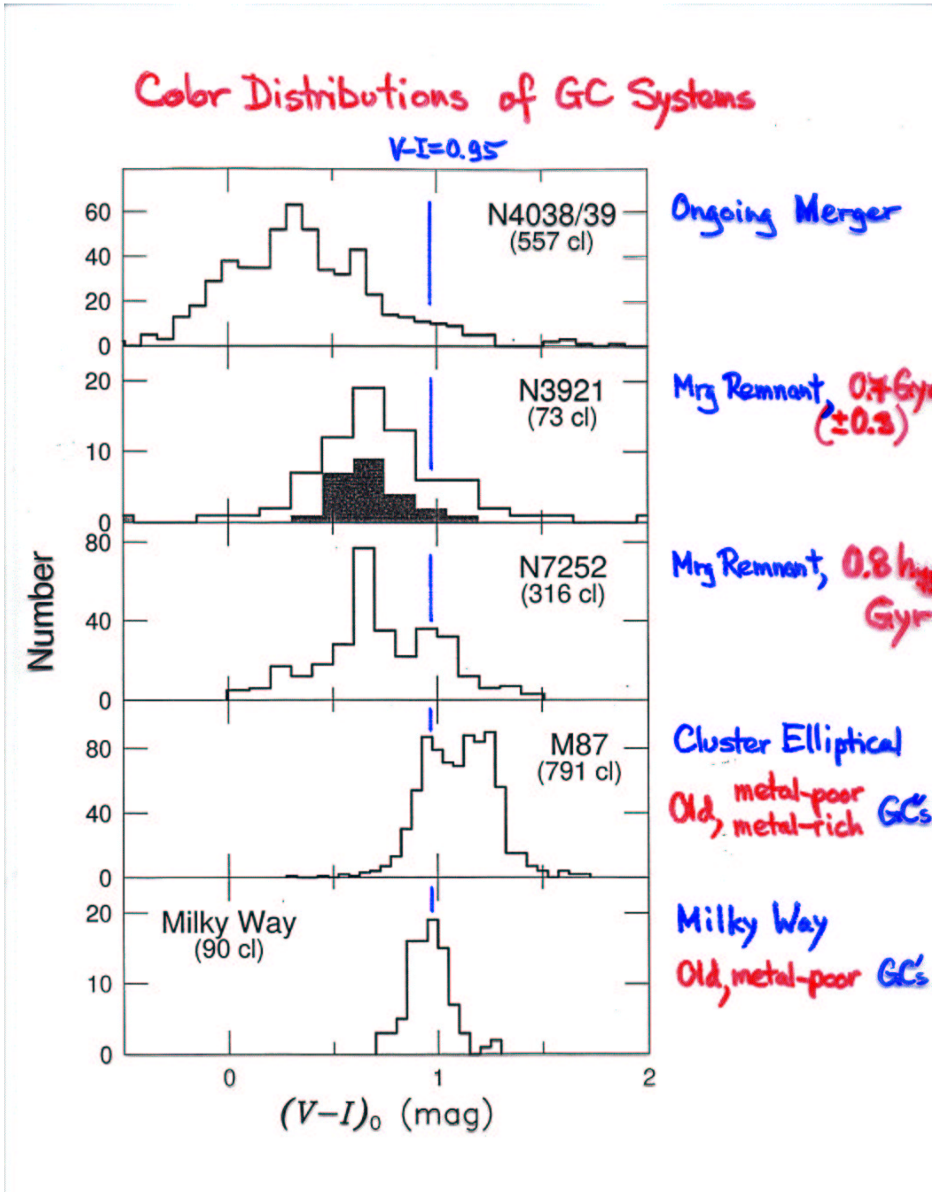
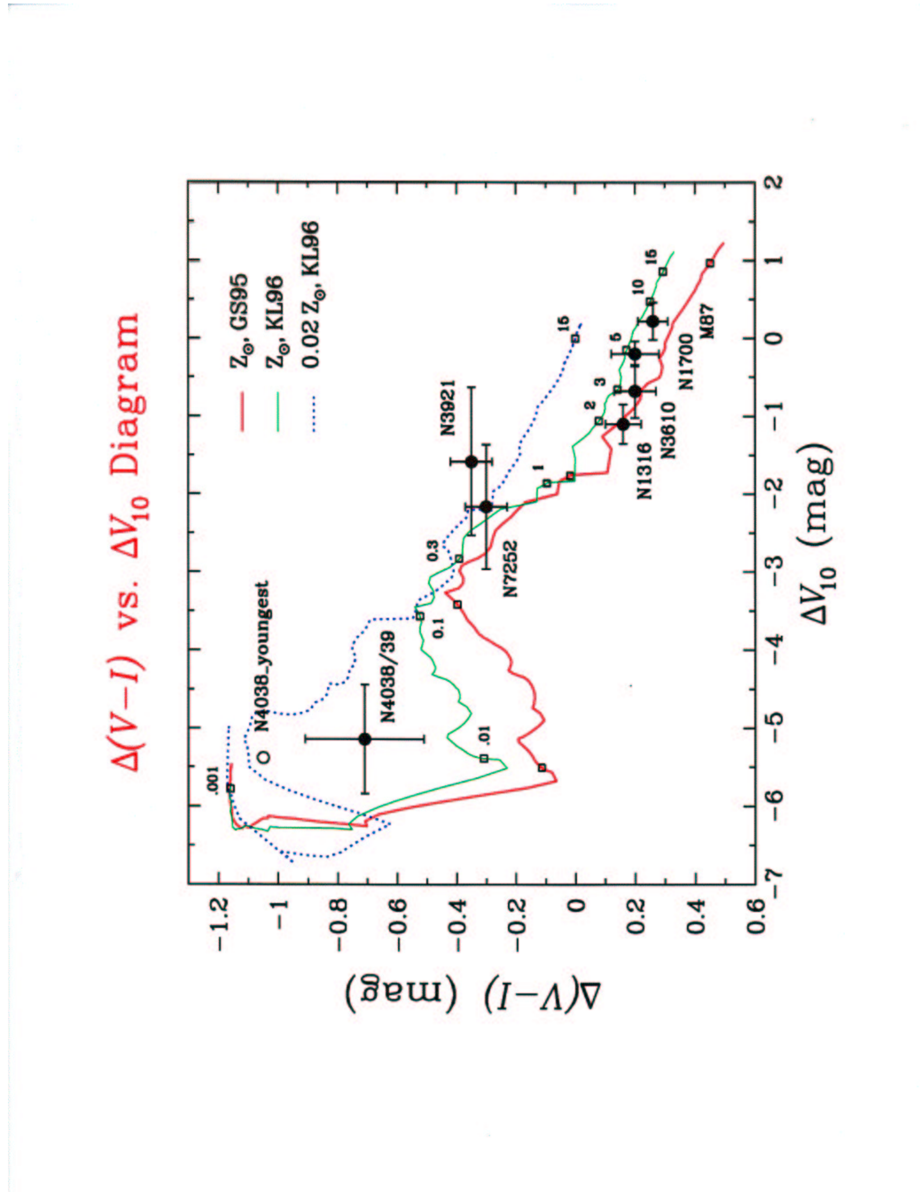


FIG. 12. (a) CMD for objects in the outer sample ($r_{proj}>6''$) with $(V-I)_c$ between 0.0 and 1.5. Background contamination has been removed statistically to show more clearly the two populations of objects.


Age Dating Young GCs in NGC 7252
N
E
S105
S101
S114
(S117)
60"
(a)
N
S105
W4
W6
W3
W10
W26
W30
W32
W31
S114
30"
(b)
12 candidates
9 useful spectra: 8 clusters, 1 background galaxy (S117)
σ_v = 140 ± 35 km s^-1 → Halo clusters

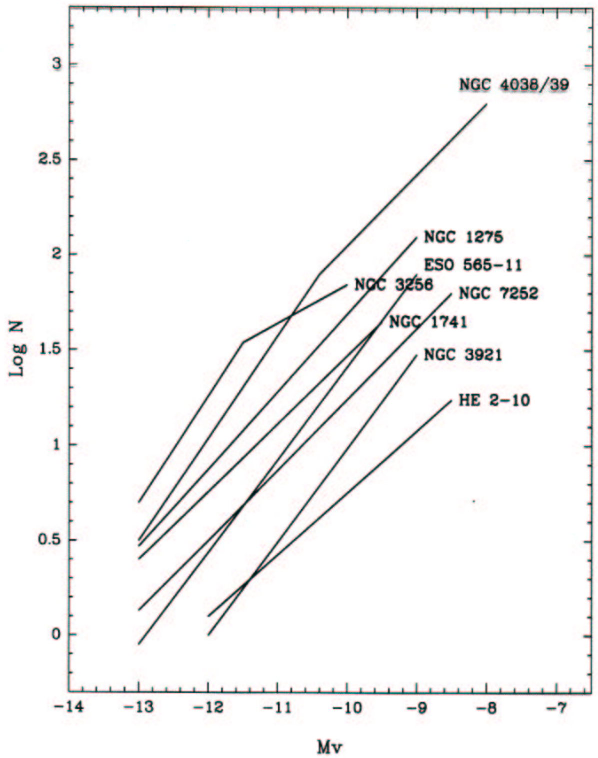

Whitmore+ 97 (simul. by Bryan Miller)
Model Simulation of 2 GC Populations
(Monte Carlo, BC96 models)
0.5 Gyr
1 Gyr
3 Gyr
10 Gyr
V-I
M_V
Young, Z⊙
15 Gyr, 0.02 Z⊙
15 Gyr, 0.02 Z⊙
Intermediate Age, Z⊙
15 Gyr, 0.02 Z⊙
10 Gyr old, Z⊙
→ At age 1-2 Gyr, the young GC's of Z⊙ turn redder than the 15 Gyr old GC's of 0.02 Z⊙


Color Distributions of GC Systems
V-I=0.95
N4038/39
(557 cl)
Ongoing Merger
N3921
(73 cl)
Mrg Remnant, 0.7 Gyr
(±0.3)
N7252
(316 cl)
Mrg Remnant, 0.8 Gyr
M87
(791 cl)
Cluster Elliptical
Old, metal-poor, metal-rich GC's
Milky Way
(90 cl)
Old, metal-poor GC's
Number
(V−I)₀ (mag)


Δ(V−I) vs. ΔV₁₀ Diagram
Z⊙, GS95
Z⊙, KL96
0.02 Z⊙, KL96
N4038_youngest
N4038/39
N3921
N7252
N1316
N3610
N1700
M87
ΔV₁₀ (mag)
Δ(V−I) (mag)

Whitmore 2003 astro-ph/0012546, STScI Symp. 14

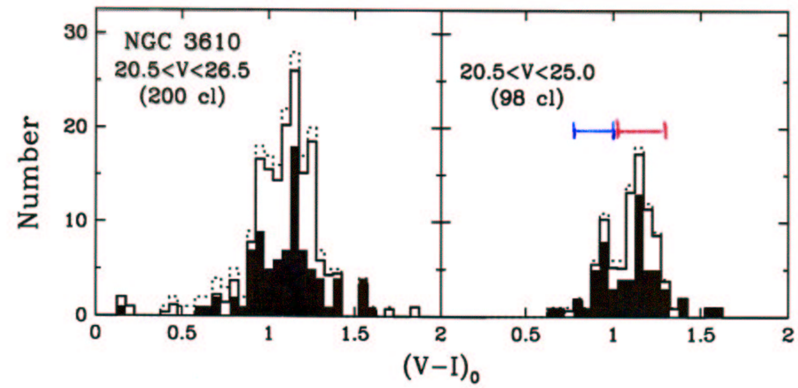
Cluster Luminosity Functions in Mergers & Starburst Galaxies



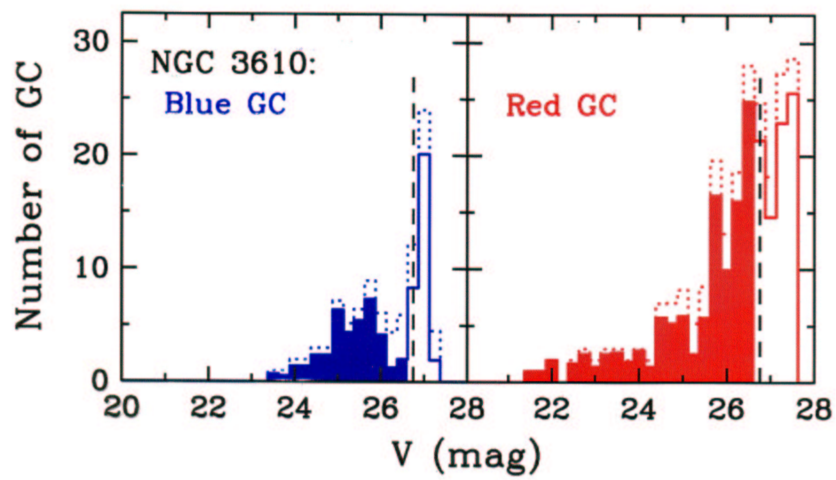
- LFs are ~power laws: $\Phi(L)\,dL \propto L^{\alpha}\,dL$, with $\alpha \approx -1.7$ to -2.1
- Tentative evidence for knee in LFs of ongoing mergers NGC 3256 (Zepf+99) and NGC 4038/39 (Whitmore+99)

NGC 3610 Globular Clusters

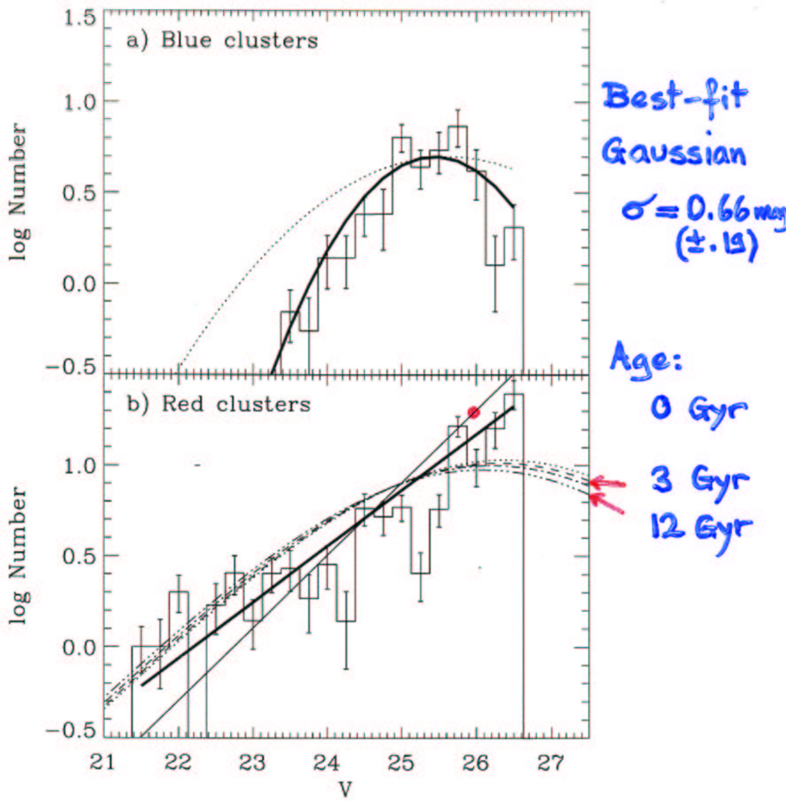
Color Distributions



Luminosity Functions

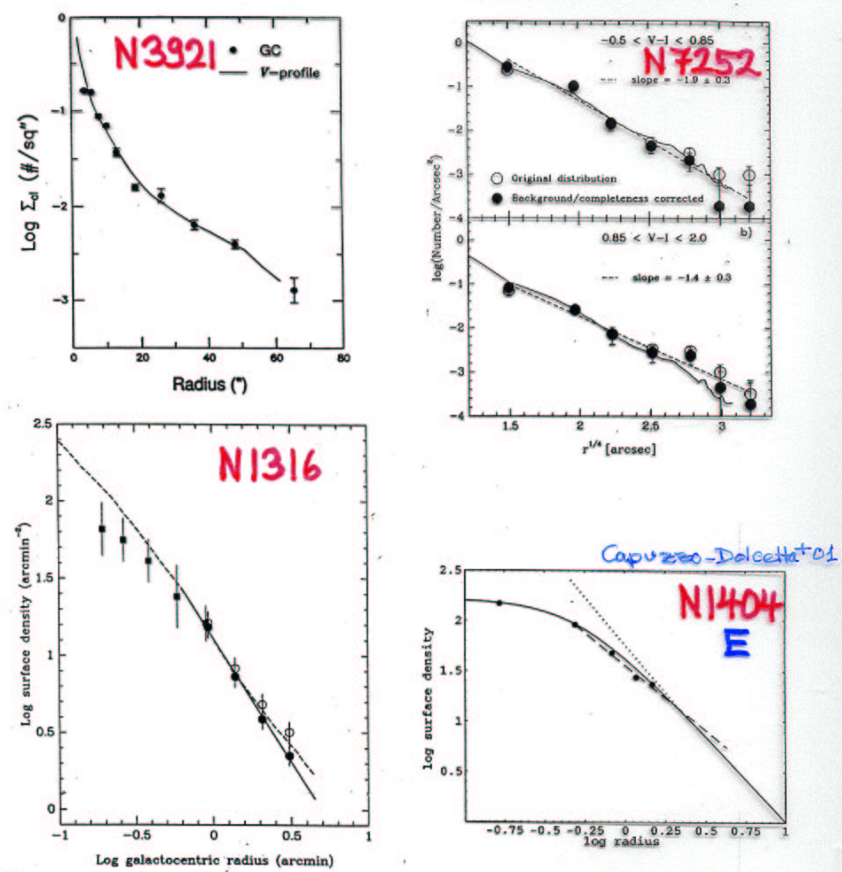


NGC 3610: Fits to Luminosity Functions



- LF of blue, metal-poor GCs is best fit by a Gaussian.
- LF of red, metal-rich GCs is best fit by a power law of slope -1.78 ± 0.05 (thick line). Model LFs with power-law IMF fit less well.
- There is no clear evidence for a turnover of the LF.

Radial Distribution: Formation, Evolution

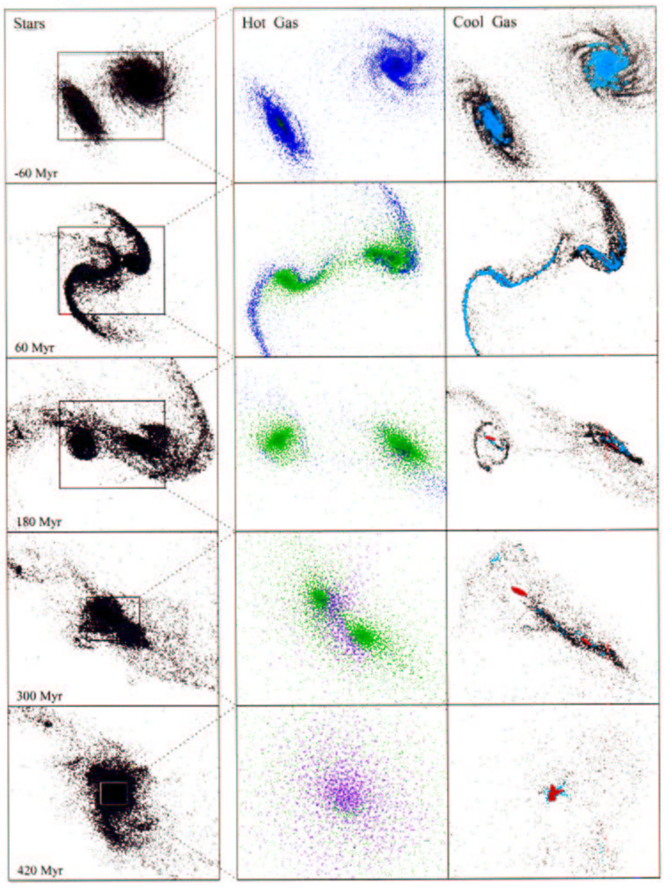


- Young GCs and/or progenitors experienced the same violent relaxation as did the average luminous matter ⇒ Progenitors were compact
- Evidence for central erosion of GC Systems

Barnes (1999)

Simulated Merger of 2 Gas-Rich Disk Galaxies

Stars Hot Gas Cool Gas



Pericenter at $t=0$

"Simple" GC Formation Scenario

- Synchronized formation of universal population of metal-poor GCs from early GMCs shocked by pressure increase due to cosmological reionization at $z \approx 7-15$ (Cen 2001). Power-law LF at birth evolves at low-mass end through evaporation, etc (Fall & Rees 77, 88).

- Later formation of metal-enriched GCs in:

  Major mergers (gas-rich: clear bimodality; gas-poor: mainly metal-poor, NGC 4406?)

  Multiple, incl. minor, mergers (more messy color distributions)

  Single minor mergers (form S0; disky distribution of metal-rich GCs)

- Complications: GCs form semi-continuously also in calmer environments (e.g., Irr, barred galaxies) and can be acquired via satellite accretions.

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CONCLUSIONS

- Gas-rich mergers form both second-generation GCs and elliptical and S0 galaxies.
- Ongoing disk mergers (e.g., Antennae) and recent merger remnants host significant populations of young ($\lesssim$1 Gyr) GCs. Age dating shows that in each case $\sim 10^2 - 10^3$ GCs formed during the merger.
- The young GCs in N7252 form a ~0.5-Gyr old, metal-rich halo population ($Z \approx Z_\odot$). They nearly double the total number of halo GCs.
- Intermediate-age, metal-rich GCs in Es like N1316 & N3610 suggest an evolutionary link between young halo GCs of N3921, N7252 and metal-rich GCs in old Es with bimodal cluster distributions. Their LFs are better described by power laws than by Gaussians.
- Second-generation GCs probably form from Giant Molecular Clouds in merging gas-rich disks, squeezed into collapse by surrounding starburst-heated gas (Jog & Solomon 1992). First-generation GCs may have formed near-simultaneously from early GMCs shocked by the cosmological reionization (Cen 2001).