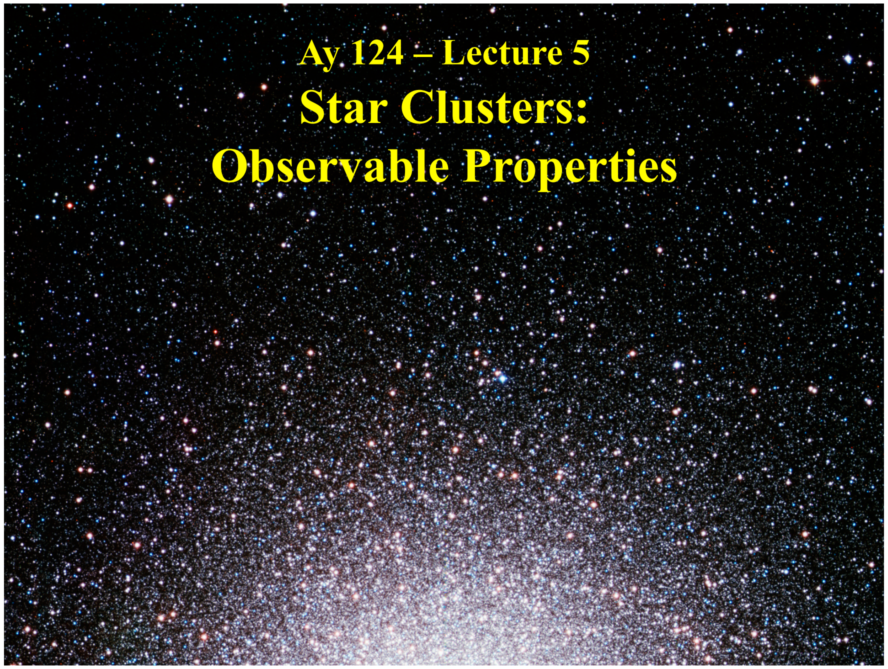


Ay 124 – Lecture 5

Star Clusters:
Observable Properties

Star Clusters (Mostly Globular)

- Definition and basic properties
- Correlations and non-correlations of cluster parameters
  - Hints about their formation
- Their stellar populations and cluster ages
- Dynamical evolution of star clusters
  - King models
  - Core collapse and the role of binaries
  - Gravothermal oscillations
  - Tidal evaporation
  - Stellar collisions and modification of stellar populations
- Formation mechanisms of globular clusters
  - Multiple stellar populations in globulars
- Open clusters
  - Their origins and demise

Star Clusters

Open (or Disk):

$N_\star \sim 10^2 - 10^3$
Ages ~ $10^7 - 10^9$ yr

Globular:

$N_\star \sim 10^4 - 10^7$
Ages ~ 10 - 13 Gyr

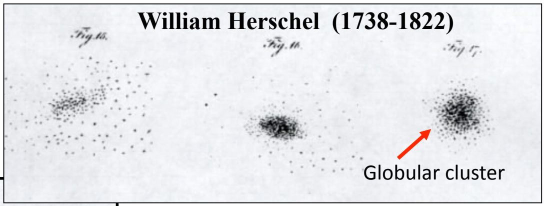
- Great "laboratories" for stellar dynamics
- Dynamical and evolutionary time scales < or << Galaxy's age, and a broad range of evolutionary states is present

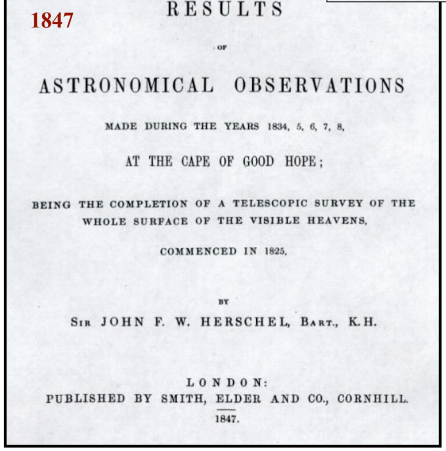
---

Basic Properties of Typical, Pressure-Supported Stellar Systems

	N	R (pc)	V_{total} (km/s)	$t_{cross}=R/v$ ($\times 10^6$ yr)	t_{relax} (yr)
Open cluster	100	2	0.5	4	8×10^6
Globular cluster	10^5	4	10	0.4	4×10^8
E Galaxy core	10^{10}	400	250	2	10^{14}
E galaxy	10^{12}	10	600	20	1×10^{17}

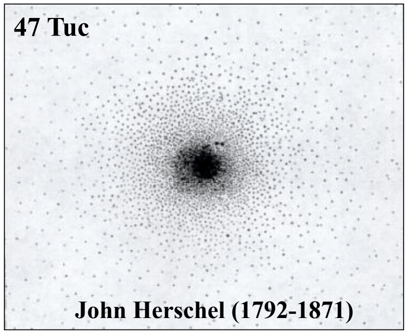
Most Galactic GC's were originally catalogued by Charles Messier and William Herschel




1847

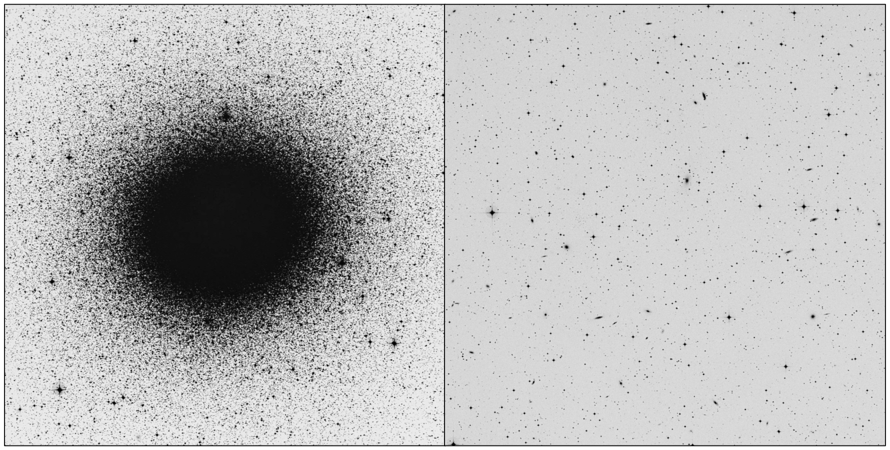
RESULTS
OF
ASTRONOMICAL OBSERVATIONS
MADE DURING THE YEARS 1834, 5, 6, 7, 8,
AT THE CAPE OF GOOD HOPE;
BEING THE COMPLETION OF A TELESCOPIC SURVEY OF THE
WHOLE SURFACE OF THE VISIBLE HEAVENS,
COMMENCED IN 1825,
BY
SIR JOHN F. W. HERSCHEL, BART., K.H.

LONDON:
PUBLISHED BY SMITH, ELDER AND CO., CORNHILL.
1847.



… and some are still being found today

The Range of GC Luminosities


Omega Cen = NGC 5139 (M_V = -10.3)   AM 4 (M_V = -1.6)

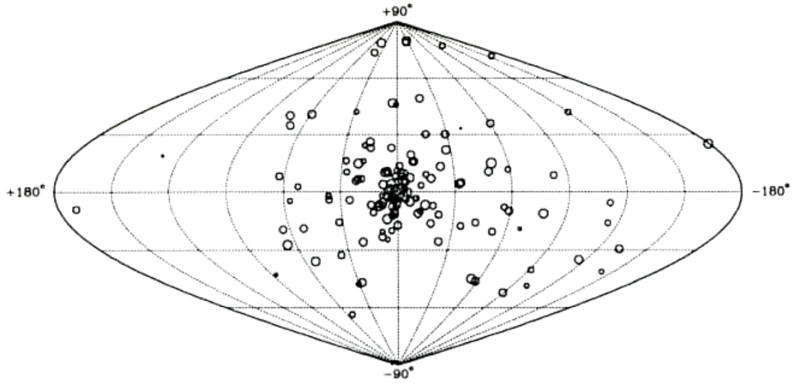
DSS Blue, FOV = 36 arcmin

Globular Cluster Properties

Table 1. Basic Facts about the Globular Clusters of the Galaxy

Number known	147
Median distance from Galactic Centre	9.3kpc
Median absolute V magnitude	-7.27
Median concentration	1.50
Median core relaxation time	3.39×10^8yr
Median relaxation time at the half-mass radius	1.17×10^9yr
Median core radius	1.32pc
Median half-mass radius	3.08pc
Median tidal radius	34.5pc
Median mass	$8.1 \times 10^4 M_\odot$
Median line-of-sight velocity dispersion	5.50km/s

Globular clusters are strongly concentrated in the Galaxy, but their system extends out to tens of kpc.
They belong to the stellar halo and thick disk populations.
They are old, and generally metal-poor: fossil evidence from the early phases of Galaxy formation.



Projected distribution of the 143 known globular clusters with Galactic coordinates

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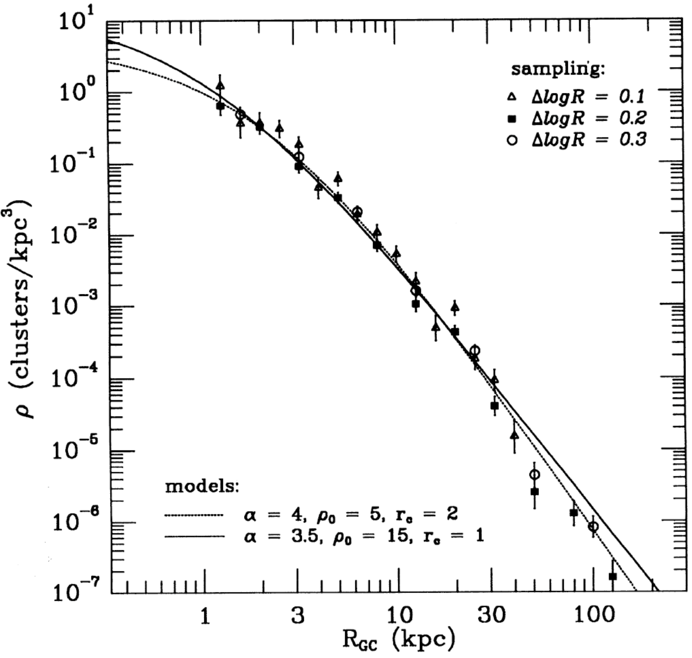
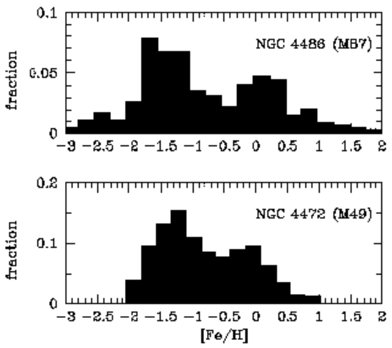
Radial Density Profile of the Galactic GC System

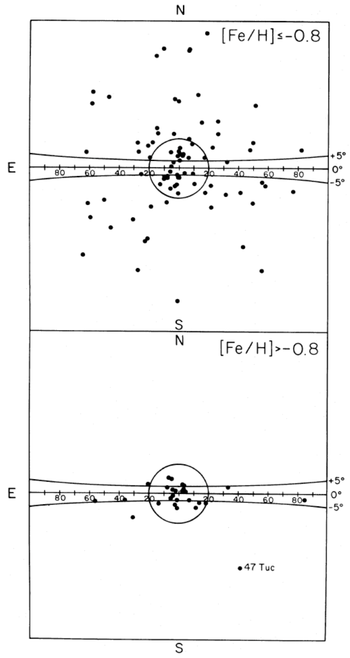


Note:
Much steeper than the dark halo profile,
$\rho \sim r^{-2}$

Disk and Halo GC Subsystems (Zinn 1985)

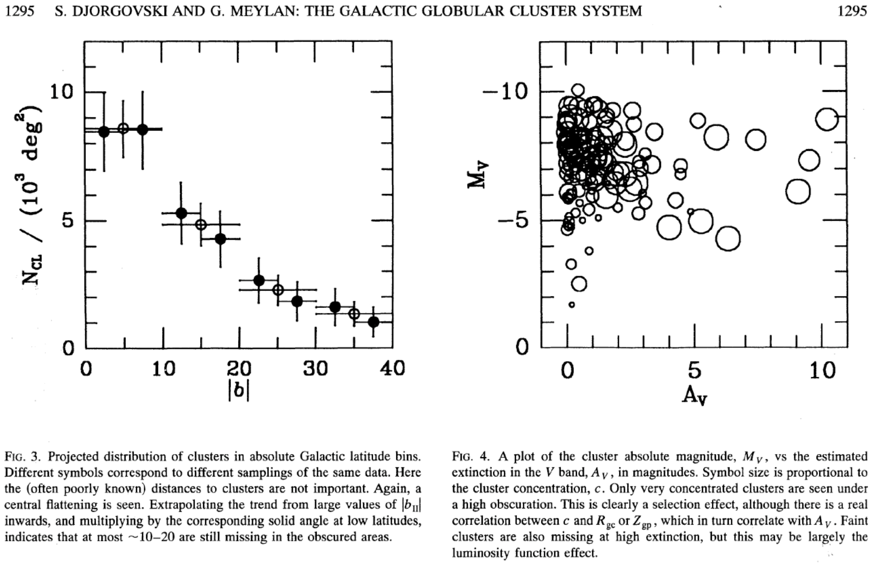
Bimodal metallicity distributions are common in globular cluster systems





Selection Effects:

- Missing clusters at low Galactic latitudes
- Missing intrinsically faint clusters far away



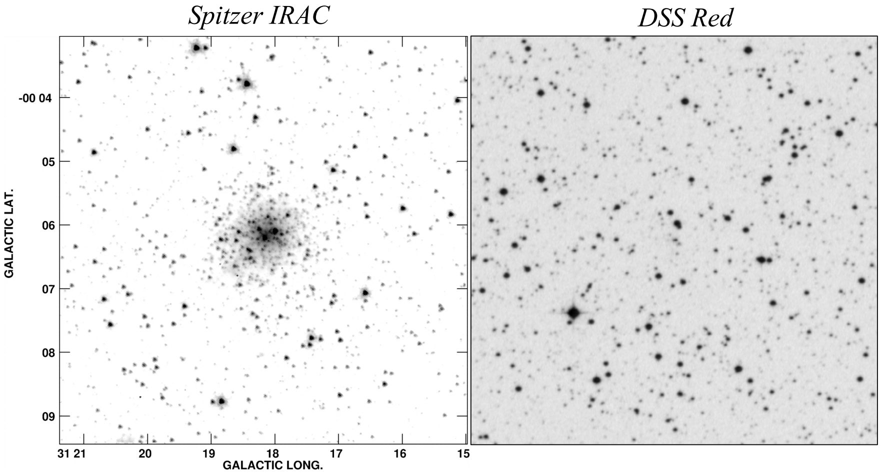
1295 S. DJORGOVSKI AND G. MEYLAN: THE GALACTIC GLOBULAR CLUSTER SYSTEM 1295

FIG. 3. Projected distribution of clusters in absolute Galactic latitude bins. Different symbols correspond to different samplings of the same data. Here the (often poorly known) distances to clusters are not important. Again, a central flattening is seen. Extrapolating the trend from large values of $|b_{II}|$ inwards, and multiplying by the corresponding solid angle at low latitudes, indicates that at most ~10–20 are still missing in the obscured areas.

FIG. 4. A plot of the cluster absolute magnitude, M_V, vs the estimated extinction in the V band, A_V, in magnitudes. Symbol size is proportional to the cluster concentration, c. Only very concentrated clusters are seen under a high obscuration. This is clearly a selection effect, although there is a real correlation between c and R_{gc} or Z_{gp}, which in turn correlate with A_V. Faint clusters are also missing at high extinction, but this may be largely the luminosity function effect.

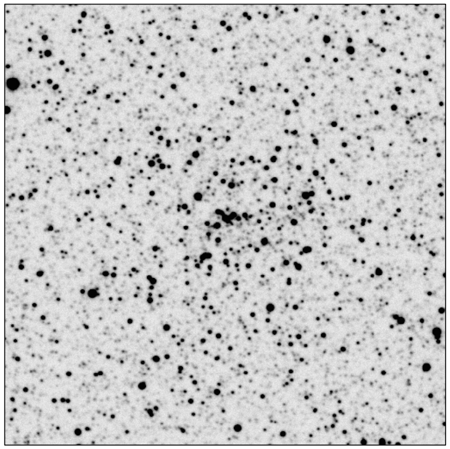
Some Recently Discovered Globulars:

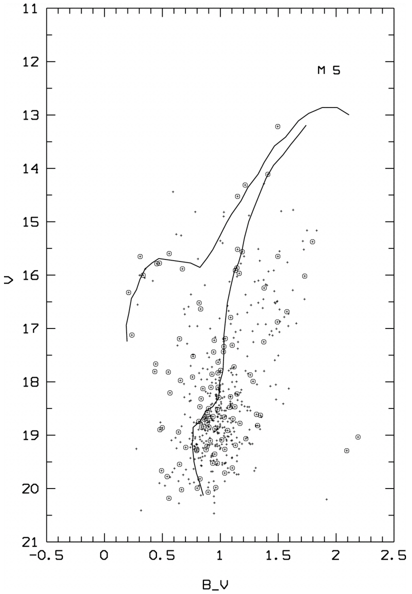
GLIMPSE C01 (Kobulnicky et al. 2005)



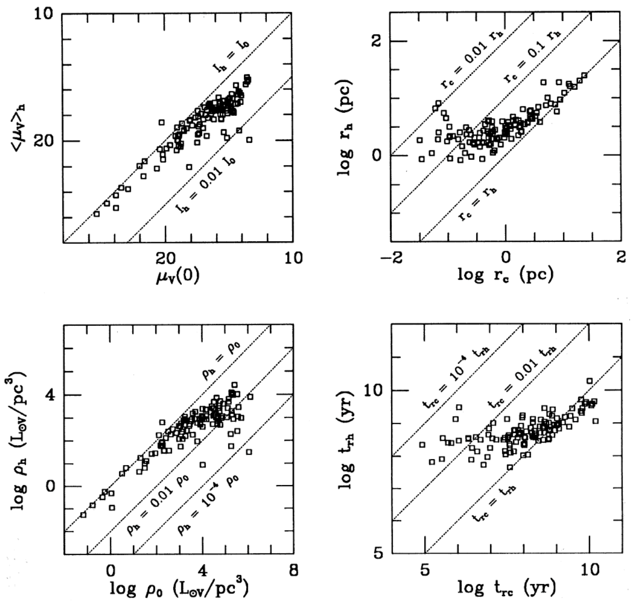
Some Recently Discovered Globulars:

AL # (Ortolani et al. 2006)

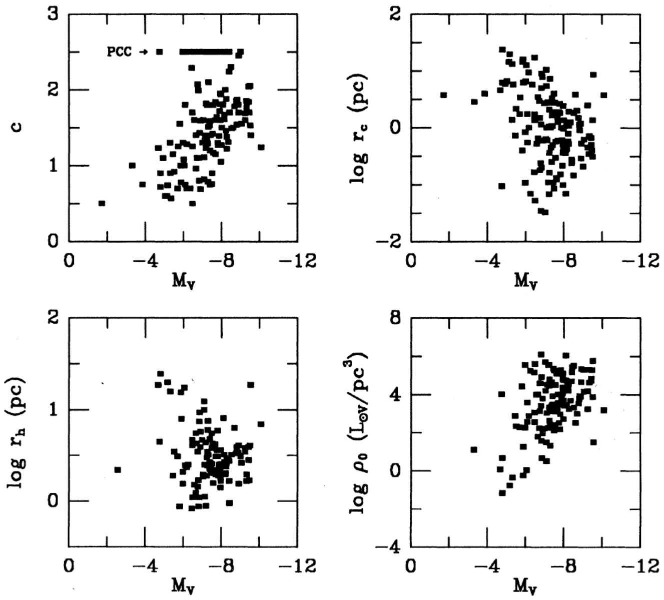




Dynamical Range of GC Parameters



Correlations of GC Parameters



Correlations of GC Parameters

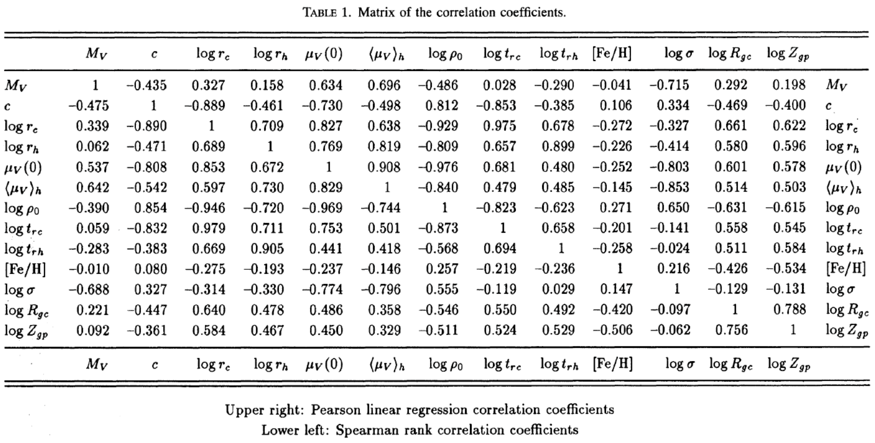


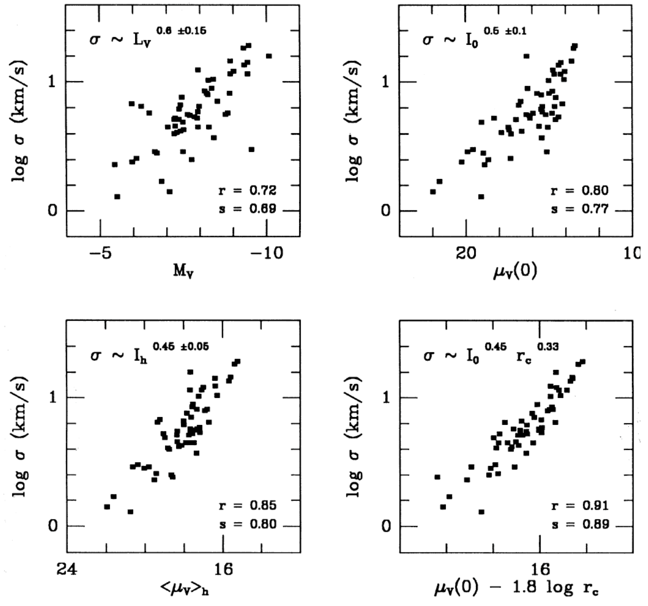
TABLE 1. Matrix of the correlation coefficients.

	M_V	c	$\log r_c$	$\log r_h$	$\mu_V(0)$	$\langle\mu_V\rangle_h$	$\log\rho_0$	$\log t_{rc}$	$\log t_{rh}$	[Fe/H]	$\log\sigma$	$\log R_{gc}$	$\log Z_{gp}$	
M_V	1	−0.435	0.327	0.158	0.634	0.696	−0.486	0.028	−0.290	−0.041	−0.715	0.292	0.198	M_V
c	−0.475	1	−0.889	−0.461	−0.730	−0.498	0.812	−0.853	−0.385	0.106	0.334	−0.469	−0.400	c
$\log r_c$	0.339	−0.890	1	0.709	0.827	0.638	−0.929	0.975	0.678	−0.272	−0.327	0.661	0.622	$\log r_c$
$\log r_h$	0.062	−0.471	0.689	1	0.769	0.819	−0.809	0.657	0.899	−0.226	−0.414	0.580	0.596	$\log r_h$
$\mu_V(0)$	0.537	−0.808	0.853	0.672	1	0.908	−0.976	0.681	0.480	−0.252	−0.803	0.601	0.578	$\mu_V(0)$
$\langle\mu_V\rangle_h$	0.642	−0.542	0.597	0.730	0.829	1	−0.840	0.479	0.485	−0.145	−0.853	0.514	0.503	$\langle\mu_V\rangle_h$
$\log\rho_0$	−0.390	0.854	−0.946	−0.720	−0.969	−0.744	1	−0.823	−0.623	0.271	0.650	−0.631	−0.615	$\log\rho_0$
$\log t_{rc}$	0.059	−0.832	0.979	0.711	0.753	0.501	−0.873	1	0.658	−0.201	−0.141	0.558	0.545	$\log t_{rc}$
$\log t_{rh}$	−0.283	−0.383	0.669	0.905	0.441	0.418	−0.568	0.694	1	−0.258	−0.024	0.511	0.584	$\log t_{rh}$
[Fe/H]	−0.010	0.080	−0.275	−0.193	−0.237	−0.146	0.257	−0.219	−0.236	1	0.216	−0.426	−0.534	[Fe/H]
$\log\sigma$	−0.688	0.327	−0.314	−0.330	−0.774	−0.796	0.555	−0.119	0.029	0.147	1	−0.129	−0.131	$\log\sigma$
$\log R_{gc}$	0.221	−0.447	0.640	0.478	0.486	0.358	−0.546	0.550	0.492	−0.420	−0.097	1	0.788	$\log R_{gc}$
$\log Z_{gp}$	0.092	−0.361	0.584	0.467	0.450	0.329	−0.511	0.524	0.529	−0.506	−0.062	0.756	1	$\log Z_{gp}$
	M_V	c	$\log r_c$	$\log r_h$	$\mu_V(0)$	$\langle\mu_V\rangle_h$	$\log\rho_0$	$\log t_{rc}$	$\log t_{rh}$	[Fe/H]	$\log\sigma$	$\log R_{gc}$	$\log Z_{gp}$	

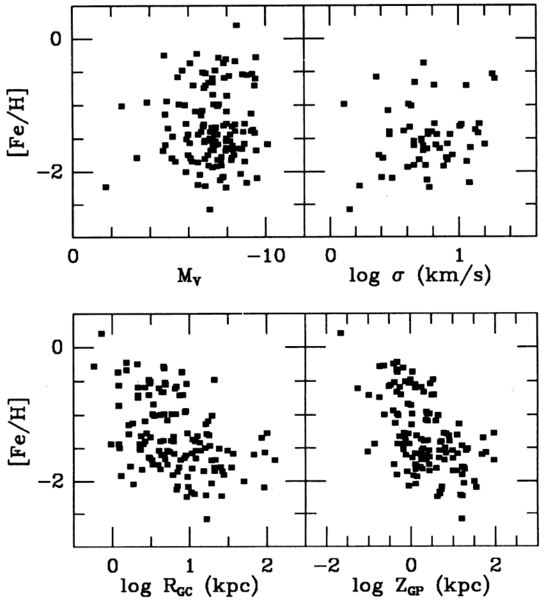
Upper right: Pearson linear regression correlation coefficients
Lower left: Spearman rank correlation coefficients

Djorgovski & Meylan 1994

Velocity Dispersion Correlations



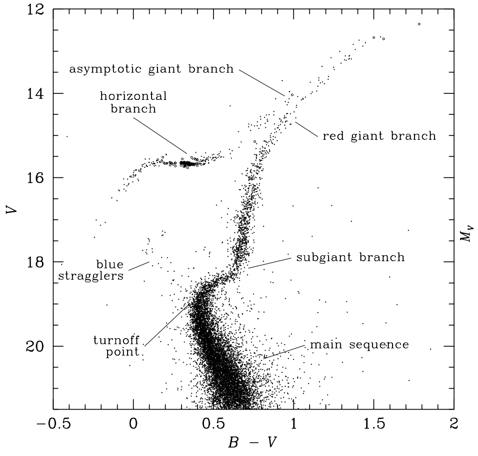
Metallicity Non-Correlations

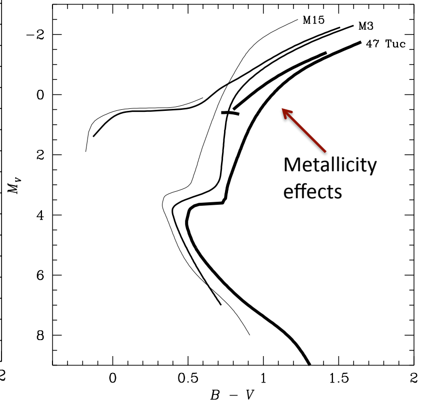


Globular clusters are *not* self-enriched (?)

Stellar Populations in Globular Clusters

- Remarkable similarities, but also some subtle differences
- Used to: (1) test the stellar evolution theory; (2) measure the ages as a cosmological constraint; (3) probe the interplay of stellar dynamics and stellar populations

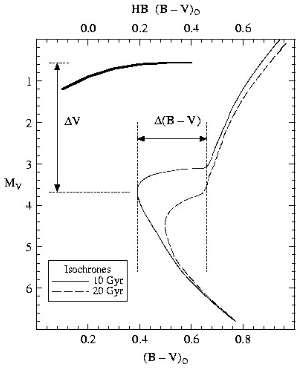




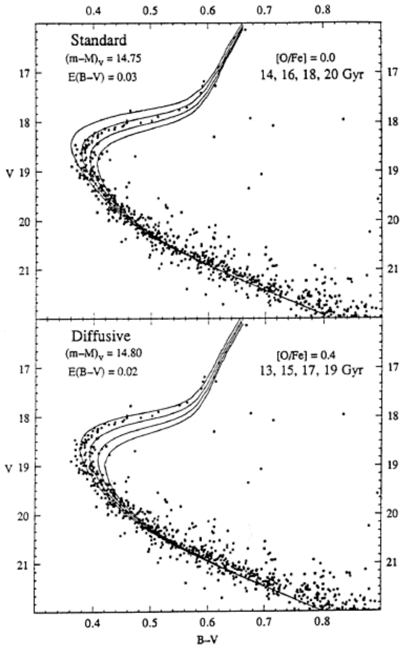
Ages of Globular Clusters

- We measure the age of a globular cluster by measuring the magnitude of the main sequence turnoff or the difference between that magnitude and the level of the horizontal branch, and comparing this to stellar evolutionary models of which estimate the surface temperature and luminosity of a stars as a function of time
- There are a fair number of uncertainties in these estimates, including errors in measuring the distances to the GCs and uncertainties in the isochrones used to derive ages (i.e., stellar evolution models)
- Inputs to stellar evolution models include: oxygen abundance [O/Fe], treatment of convection, He abundance, reaction rates of $^{14}N + p \rightarrow {}^{15}O + \gamma$, He diffusion, conversions from theoretical temperatures and luminosities to observed colors and magnitudes, and opacities; and especially ***distances***

Globular Cluster Ages

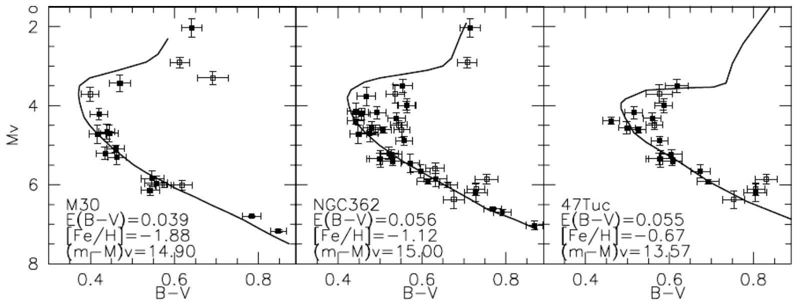


Schematic CMD and isochrones



Examples of actual model isochrones fits

Globular Cluster Ages From Hipparcos Calibrations of Their Main Sequences



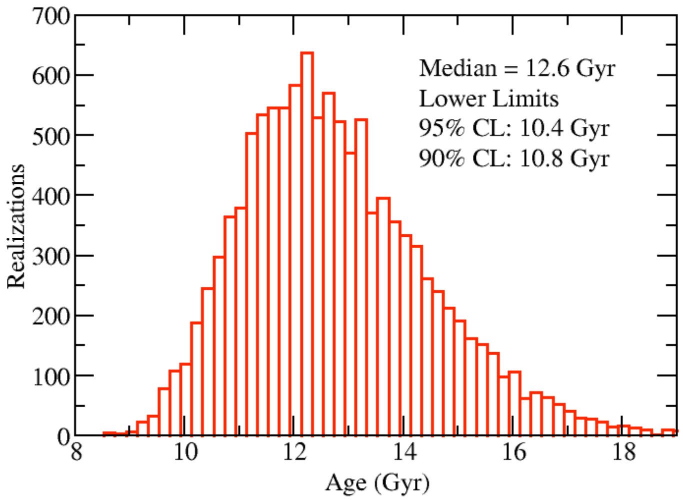
Examples of g.c. main sequence isochrone fits, for clusters of a different metallicity (Graton et al.)

The same group has published two slightly different estimates of the mean age of the oldest clusters:

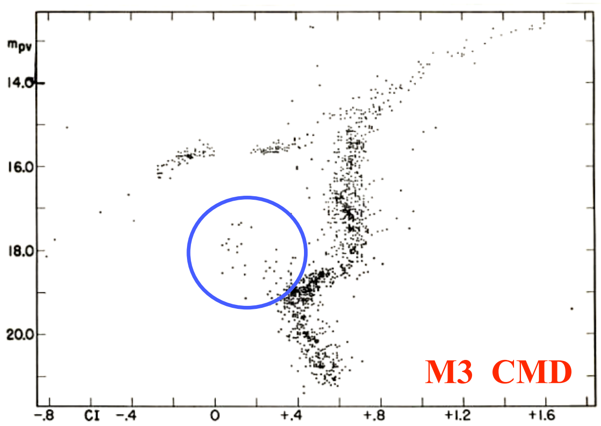
$$\mathrm{Age} = 11.8^{+2.1}_{-2.5}\mathrm{Gyr}$$

$$\mathrm{Age} = 12.3^{+2.1}_{-2.5}\ \mathrm{Gyr}$$

Range of possible GC ages (Chaboyer & Krauss 2003)



Blue Stragglers: Stellar Merger Products?



Commonly seen in globular clusters, as an extension of the main sequence, and with masses up to twice the turnoff mass

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White Dwarf Cooling Curves

- White dwarfs are the end stage of stellar evolution for stars with initial masses < 8 $M_\odot$
- They are supported by electron degeneracy pressure (not fusion) and are slowly cooling and fading as they radiate
- We can use the luminosity of the faintest WDs in a cluster to estimate the cluster age by comparing the observed luminosities to theoretical cooling curves
- Theoretical curves are subject to uncertainties related to the core composition of white dwarfs, detailed radiative transfer calculations which are difficult at cool temperatures
- White dwarfs are faint so this is hard to do. Need deep HST observations
- Only been done for one globular cluster, consistent with the ages of GCs found from the main sequence turnoff luminosities, would be nice if there were more

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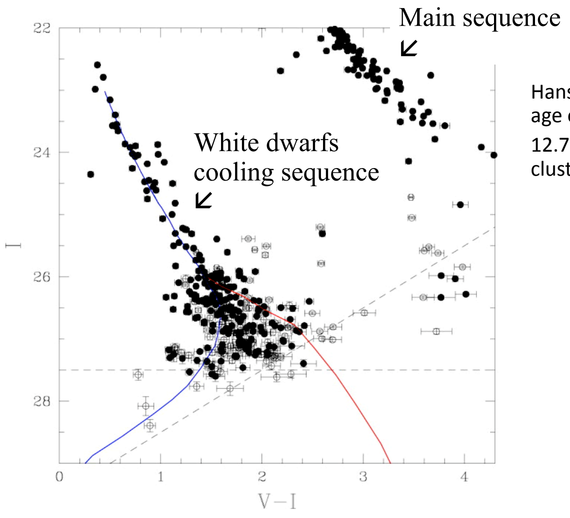
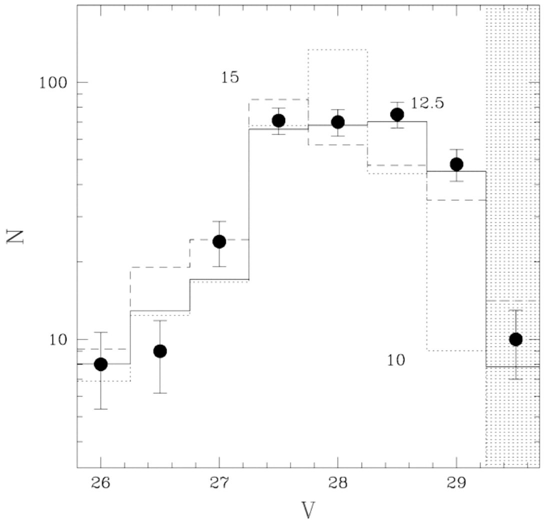
An Example: White Dwarf Sequence of M4



Hansen *et al*. (2002) find an age of 12.7 ± 0.7 Gyr for the globular cluster M4

Blue = hydrogen atmosphere models
Red = helium atmosphere models
for a 0.6 $M_\odot$ WD

An Example: WD Luminosity Function of M4



Observed WD luminosity function compared to theoretical predictions for various ages from Hansen *et al.* (2002)

Characteristic Dynamical Time Scales:

Crossing time $t_c \sim 10^6$ yr
Relaxation time $t_r \sim 10^8$ yr
Evolution time $t_e \sim 10^{10}$ yr

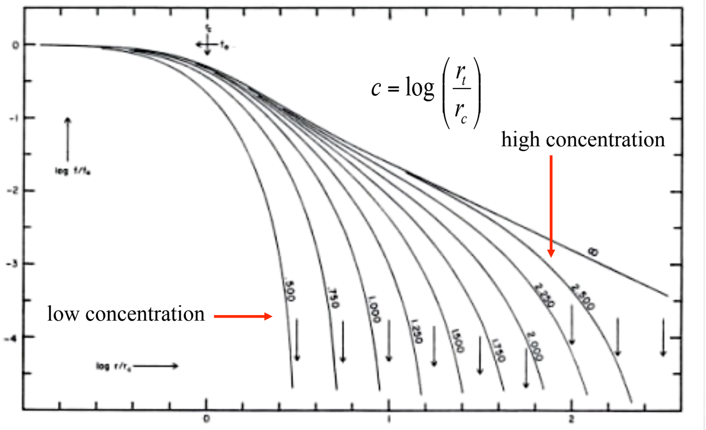
Open clusters: $t_c \sim t_r < t_e$ ➔ quickly dissolved

Globular clusters: $t_c << t_r << t_e$ ➔ a variety of dynamical evolution states must be present

Ellipticals: $t_c << t_r \sim t_e$ ➔ dynamical evolution not driven by 2-body relaxation

GCs represent an interesting class of dynamical stellar systems in which various dynamical processes take place on timescales shorter then the age of the universe. Thus, they are unique laboratories for learning about 2-body relaxation, mass segregation from equipartition of energy, stellar collisions and mergers, core collapse, etc.

King Models: A Good Description of GC Structure



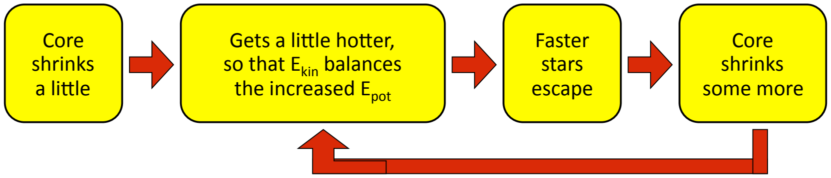
$c = \log\left(\frac{r_t}{r_c}\right)$

high concentration

low concentration

Assume isotropic, Maxwellian velocity distribution, in a cluster embedded in the Galactic tidal field. Parametrized by the mass, concentration (alias central potential), and tidal radius.

Core Collapse, aka The Gravothermal Catastrophe

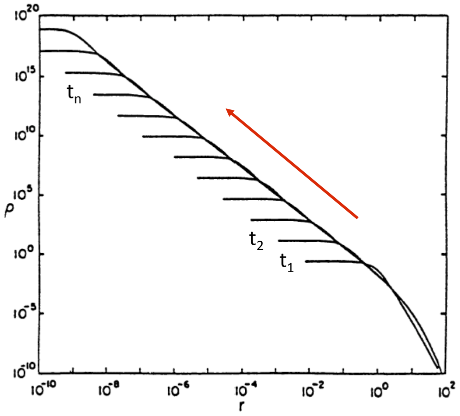


Core shrinks a little ➔ Gets a little hotter, so that E_{kin} balances the increased E_{pot} ➔ Faster stars escape ➔ Core shrinks some more

The only way to arrest the collapse is to provide *a source of energy* in the center, to replace the escaped heat.
In the case of (proto)stars, this is accomplished by thermonuclear reactions.
In the case of globular clusters, it is accomplished by ***hard binaries.***

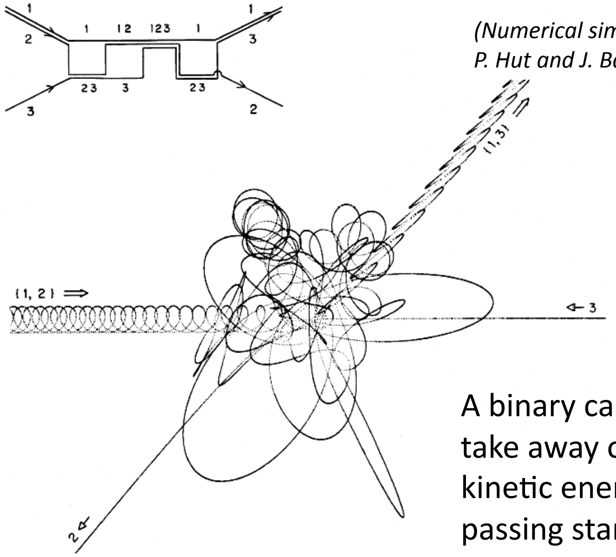
Evolution Towards the Core Collapse

King models are quasi-stationary. However, above a certain concentration, they become gravothermally unstable. The core shrinks, and the concentration increases. The density profile becomes a power-law cusp.



(Numerical simulation of a collapsing cluster, from H. Cohn)

Examples of 3-Body Interactions



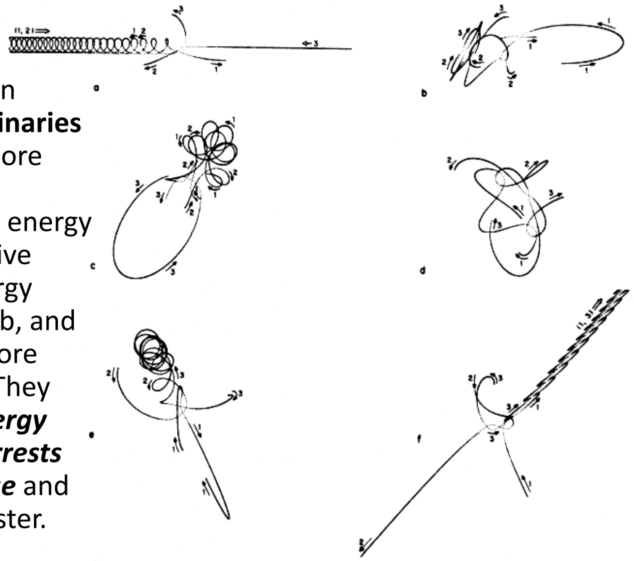
(Numerical simulation by P. Hut and J. Bahcall)

A binary can either take away or give kinetic energy to a passing star

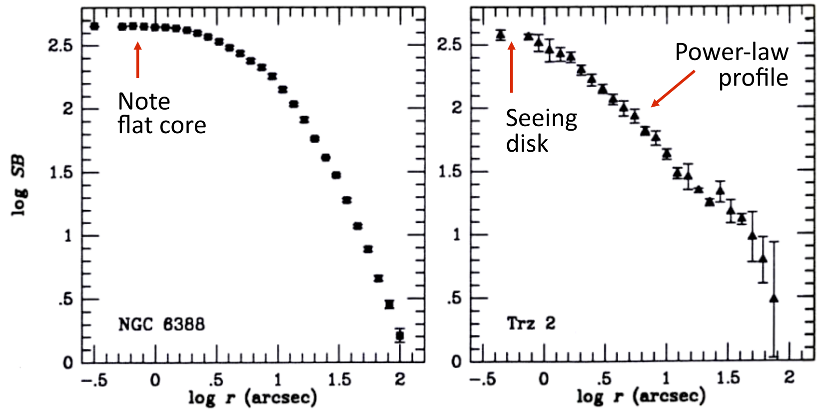
---

Examples of 3-Body Interactions

All types of interactions can occur, but on average, **hard binaries** (those bound more tightly than the average binding energy in the cluster) give away more energy than they absorb, and become ever more tightly bound. They serve as the ***energy source which arrests the core collapse*** and stabilize the cluster.



GC Surface Brightness Profiles: The Evidence for Core Collapse



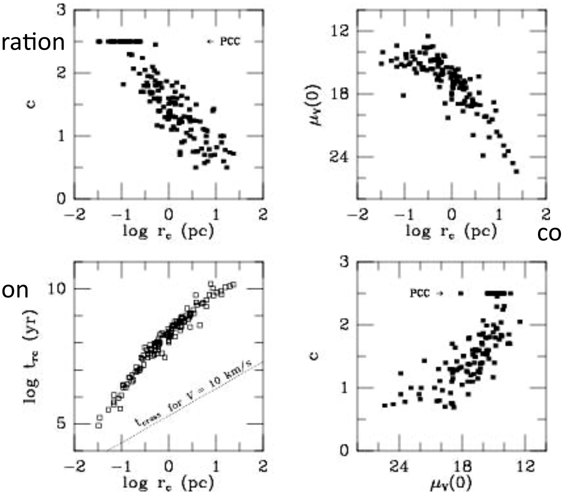
Note flat core

Seeing disk

Power-law profile

About 20% of all Galactic globulars show cuspy cores.

Core Properties of Globular Clusters: Driven by the Evolution Towards the Core Collapse?



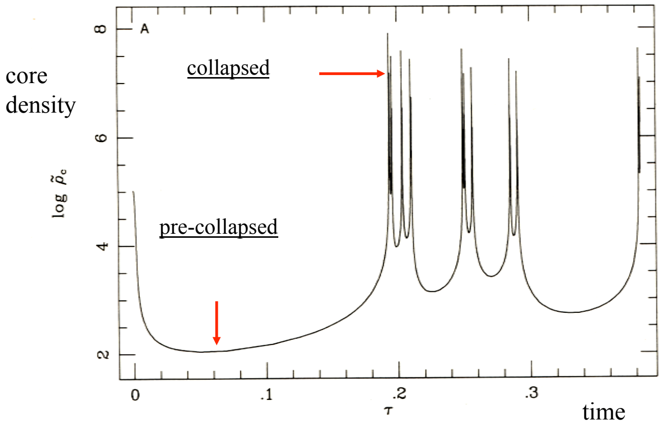
concentration

central surface brightness

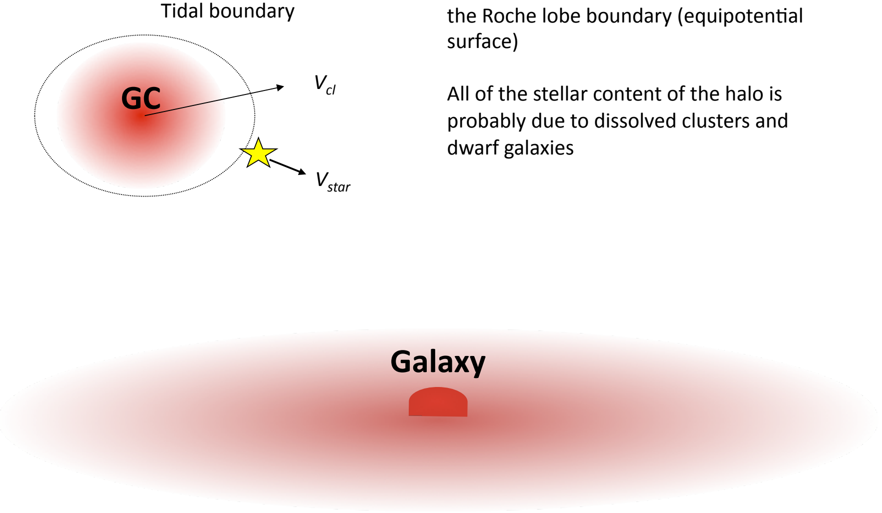
core radius

central relaxation time

The Process Can Repeat Itself in Gravothermal Oscillations: Core Collapse ➔ Bounce ➔ Collapse …



Tidal Evaporation of Globular Clusters



Stars evaporate from a cluster as they cross the Roche lobe boundary (equipotential surface)

All of the stellar content of the halo is probably due to dissolved clusters and dwarf galaxies

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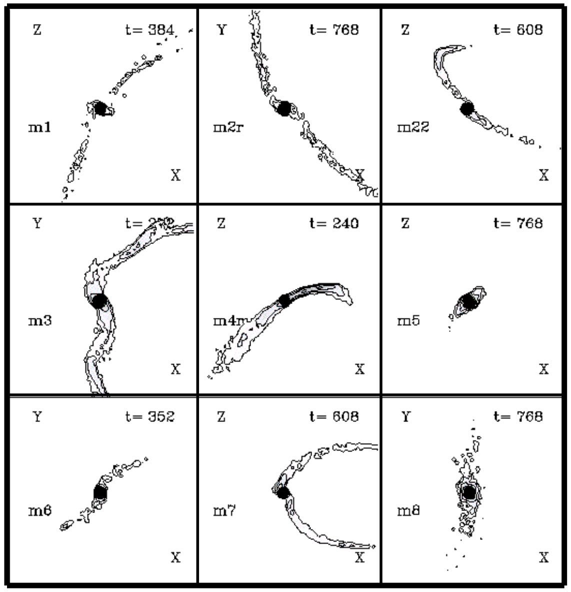

Combes et al., 1999, A&A, 352, 149

N-body simulations of globular clusters tides

Once the particles are unbound, they slowly drift along the GC path and form 2 huge tidal tails

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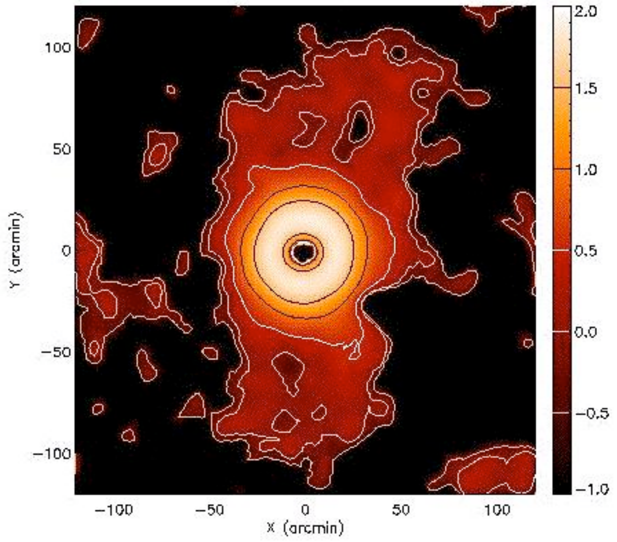
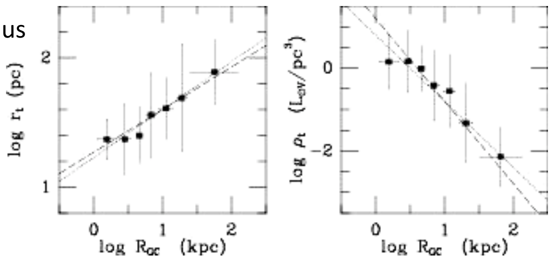
ω Centauri: Overdensities of Tidal-Tail Stars

5° x 5°

filtered image



GC Tidal Radii and Densities Depend on the Distance to the Galactic Center



tidal radius

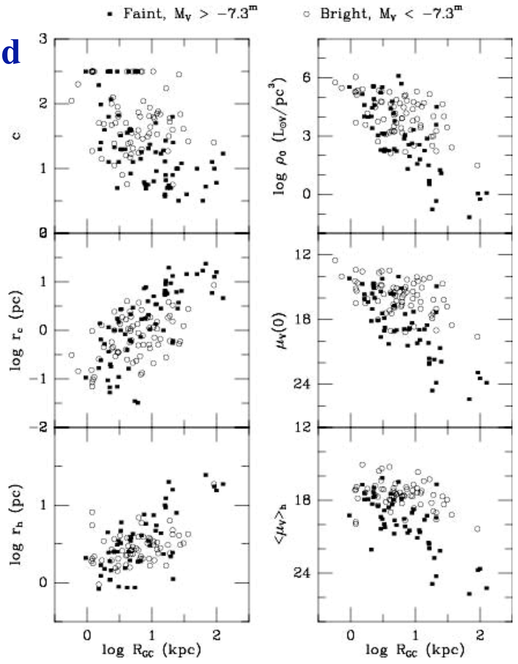
mean density

distance to the Galactic center

The trend follows the halo density profile, $\rho \sim R^{-2}$, as may be expected.

Cluster tidal radii are set by the mean density at the perigalacticon of their orbit.

GC Properties Depend on Their Position in the Galaxy



More concentrated and denser clusters are found closer to the Galactic center and plane.

They are more likely to last in the tidal field, and tidal shocks also accelerate the evolution towards the core collapse.

Tidal Dissolution of Open Clusters