Blue Hook Stars in Globular Clusters

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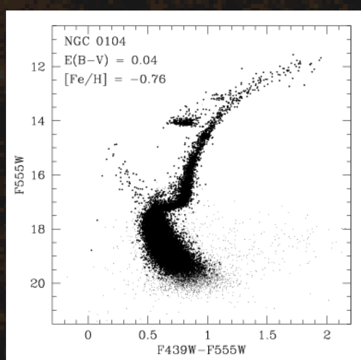
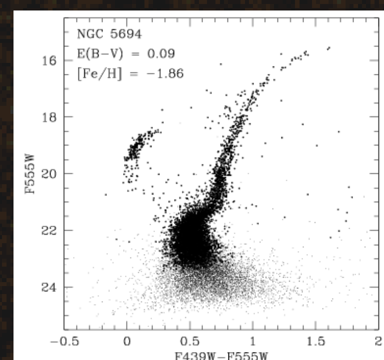
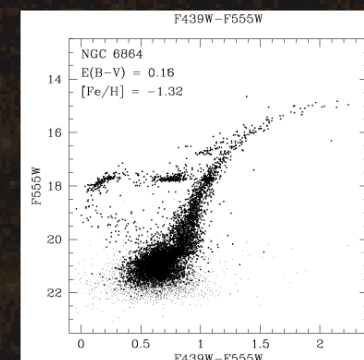
The Horizontal Branch

HB represents He core burning phase of stellar evolution

- ***He core roughly constant along HB***
- ***Initial position determined by mass of H envelope***
- ***M_{env} & T_{eff} sequence***







Piotto et al. (2002)

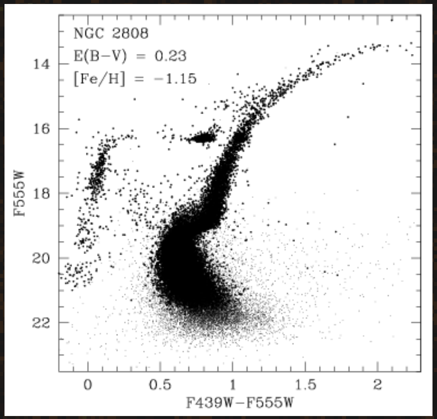
Red HB — *Metal-rich, young*

Blue HB — *metal-poor, old*

bimodal HB

- ***Physical mechanism not well understood (mass loss, He abundance, ...)***

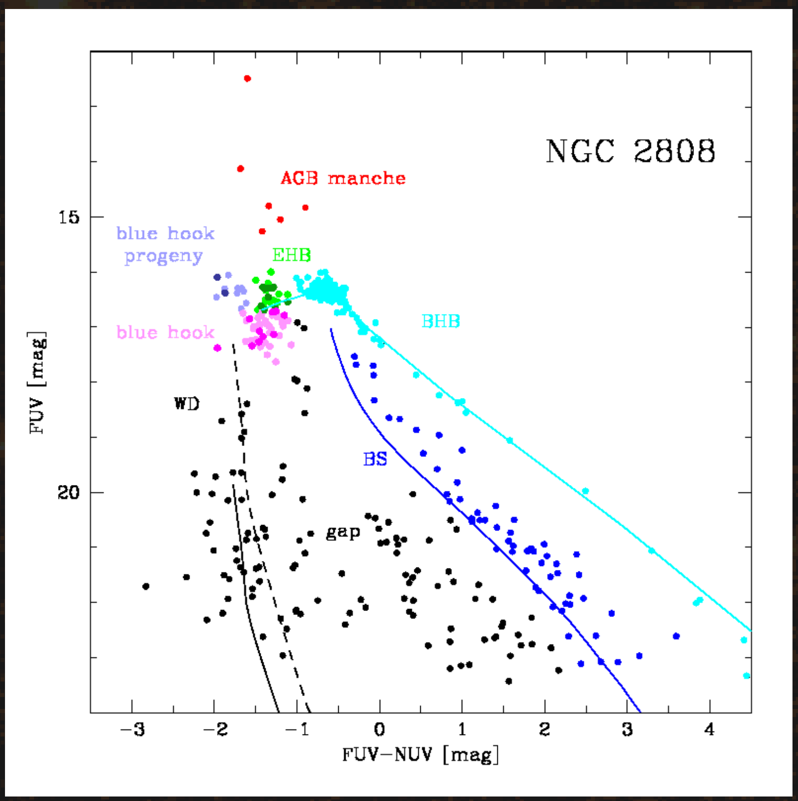
The Horizontal Branch

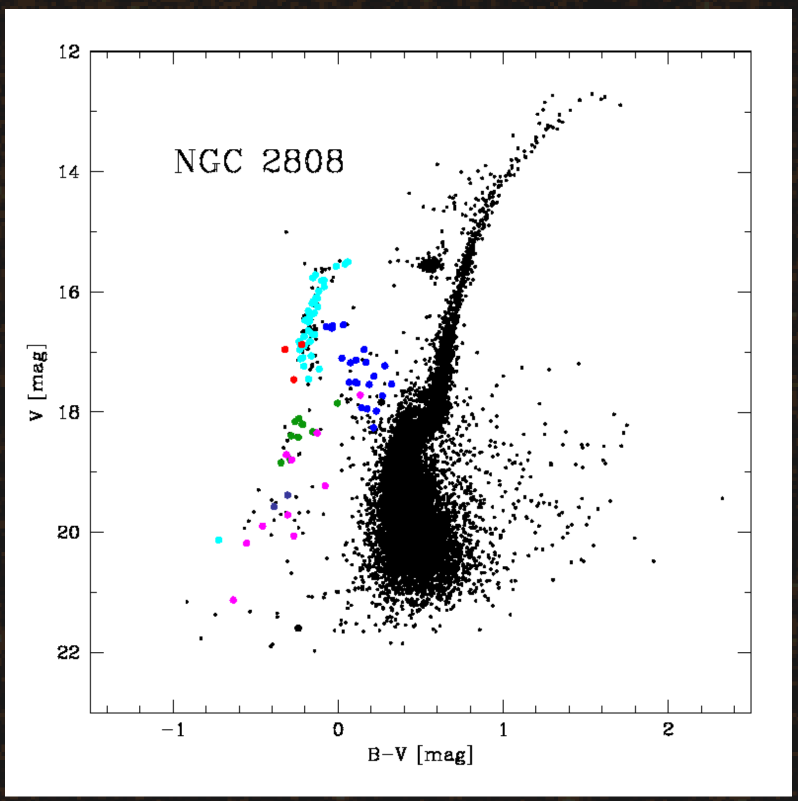


- Blue Tail (BT)
  - Very small H envelopes
    → mass loss (how?)
  - Gaps along the BT
- BT extended to EHB
  - Hotter than T_{eff} > 20,000 K (e.g. Brown et al. 2001)
  - GC counterparts to field sdB star
  - Do not return to AGB
  - Evolve into AGB-manqué or post-early AGB stars
- Blue Hook stars
  - Hotter than canonical EHB
  - Below (fainter) the EHB sequence
  - Only very few GCs

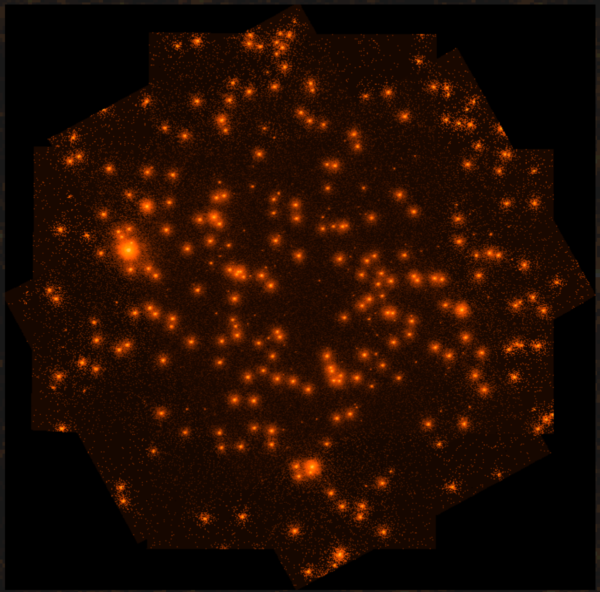
- *First detected in FUV CMD of ω Cen and NGC 2808*
- *FUV CMD: FUV fainter than the EHB stars → Blue Hook*
- *Hotter than canonical end of EHB sequence*
- *Fainter than hot end of EHB sequence in optical CMDs*

→ Identification of BHk stars much more difficult!

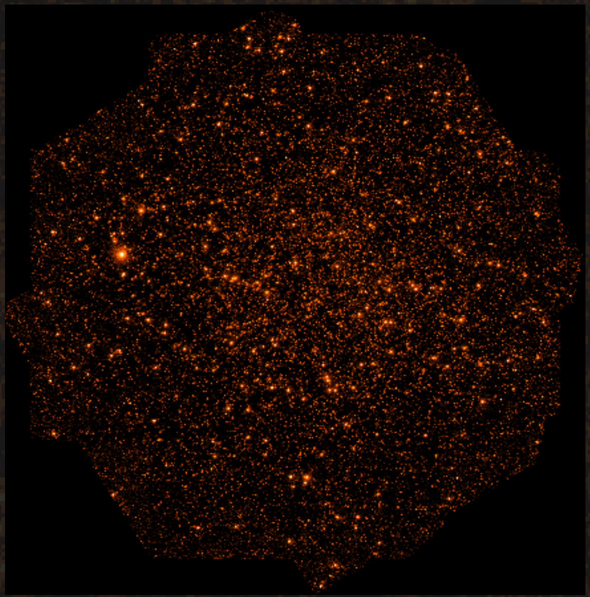




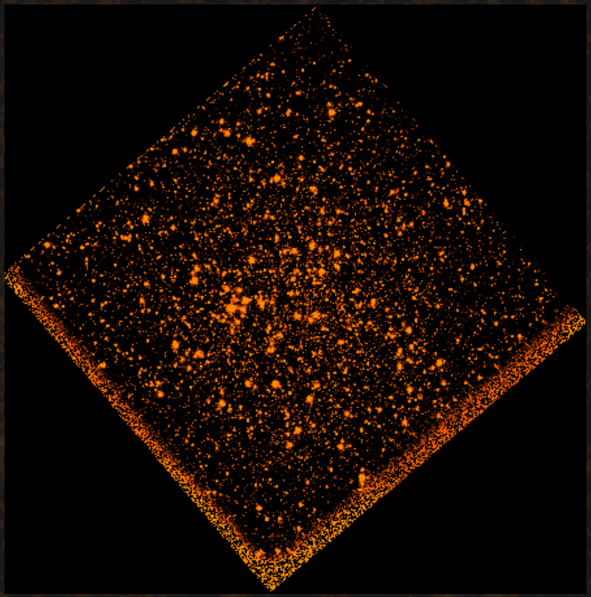
NGC 2808: from FUV to V



FUV

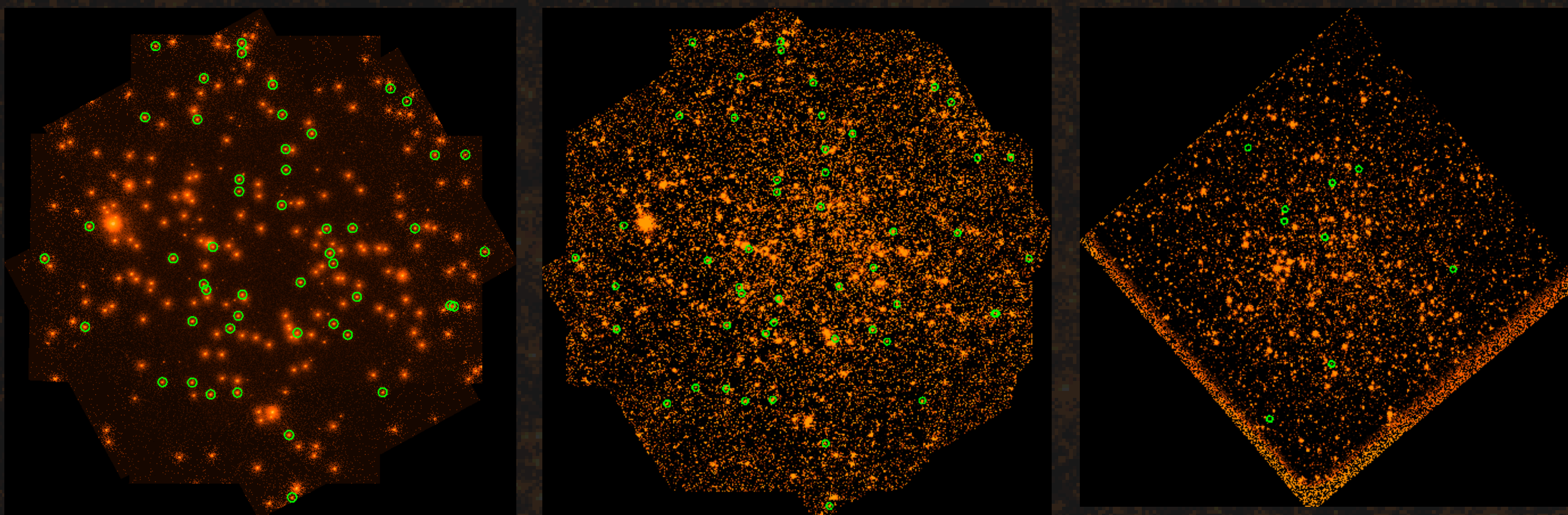


NUV



V

NGC 2808: from FUV to V



- BHk stars are FUV bright → easy to recognize
- BHk stars are optically faint → only very deep & accurate studies

How do BHk stars form?

Late He flasher scenario: *(e.g. Brown et al. 2001)*

- *Mass loss during RGB phase prevents He flash at the tip of the RGB*
- *Late He flash while star is descending the WD cooling sequence*
- *Due to thin envelope, He is mixed into envelope and H into core (flash-mixing)*

  → Enhanced He and C abundance in envelope

  (confirmed by Möhler et al. 2007)
- *As a result, BHk stars are hotter (T_{eff} > 37,500 K) and fainter in the FUV than canonical EHB stars (T_{eff} ≈ 31,500 K)*
- *Can explain BHk stars and high temperature EHB gap in optical CMD of NGC 2808*

How do BHk stars form?

He self-enrichment scenario: (e.g. Lee et al. 2005)

- EHB and BHk stars from normal evolution of He-enriched sub-populations in GCs
- Sub-populations from ejecta of first generation AGB stars
- He-enriched HB stars are bluer than normal HB stars of same age & metallicity (Lee et al. 1994)
- Could explain HB morphology and BHk stars in ω Cen and NGC 2808
- Also predicted multiple MS, which was later found (D'Antona et al. 2005, Piotto et al. 2007)

Is the presence of BHk stars associated with any particular cluster properties?

- *He self-enrichment → only GCs that exceed a critical mass threshold*
- *Late He-flash → is the required mass loss due to dynamical processes, e.g. Binary interaction?*

→ cluster sample in which the presence/ absence of BHk populations can be established with confidence

- *Only GCs with available FUV/NUV CMDs*
- *Only two optical studies: NGC 2419 & M 54*

  (Sandquist & Hess 2008, Rosenberg et al. 2004)

GC sample that could be searched for BHk poplulations

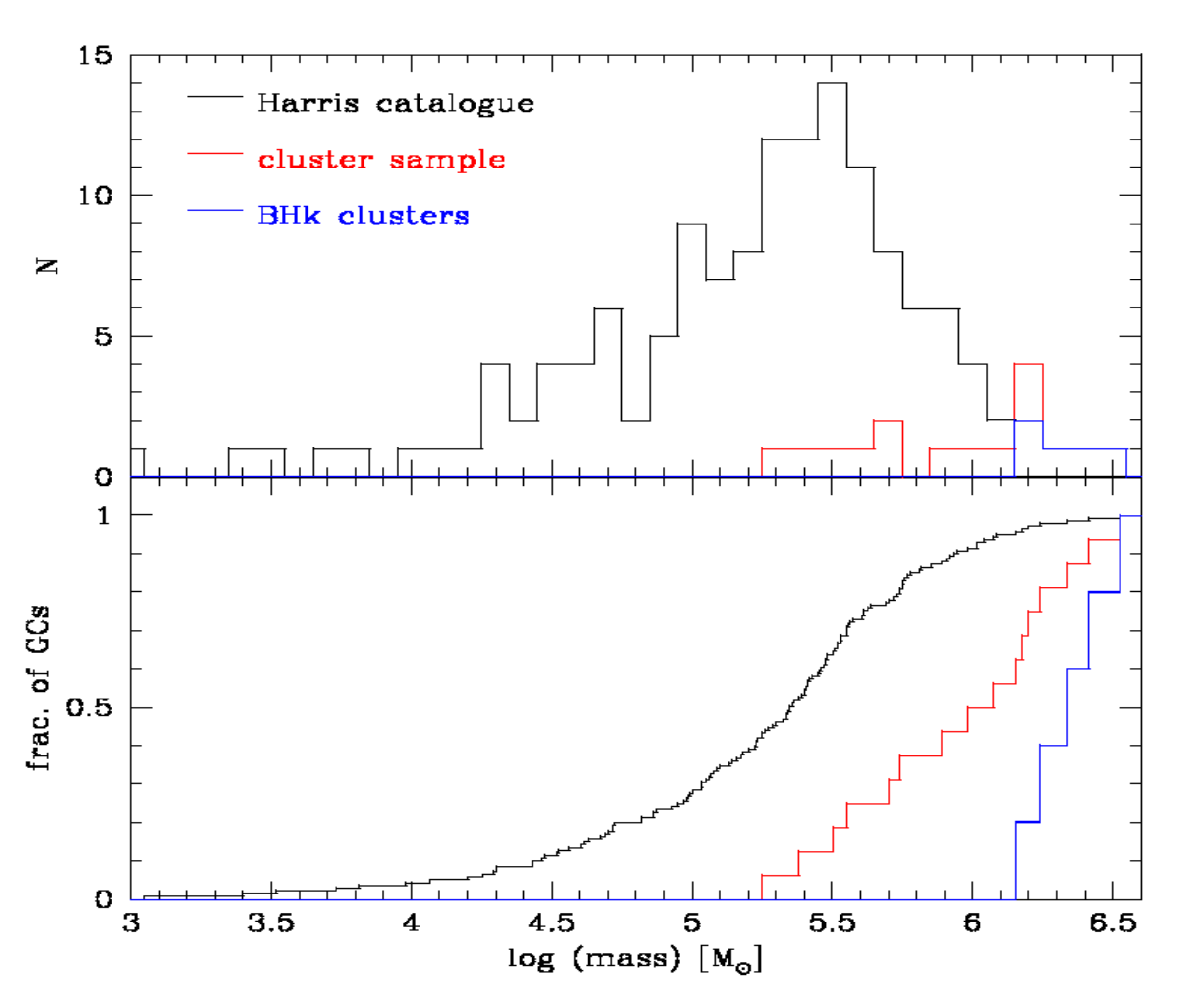
cluster	[Fe/H]	r_c [pc]	r_{hm} [pc]	r_{tidal} [pc]	c	e	$lg(t_c)$	$lg(t_{hm})$	$lg(\rho_c)$	M_{tot} [$10^6 M_\odot$]	v_c [km/s]	v_{hm} [km/s]	Γ	BHB	EHB	BHk	mp
NGC2419	-2.12	8.57	17.88	214.07	1.40	0.03	9.96	10.55	1.54	1.74	27.8	19.6	0.003	y	y	y	
NGC2808	-1.15	0.73	2.12	43.42	1.77	0.12	8.30	9.13	4.59	1.42	72.8	45.8	0.912	y	y	y	y
ωCen	-1.62	2.16	6.44	87.93	1.61	0.17	9.05	10.00	3.37	3.35	60.4	44.0	0.119	y	y	y	y
NGC6388	-0.61	0.35	1.95	18.06	1.70	0.01	7.74	9.08	5.34	2.17	124.0	80.2	2.810	y	y	y	HB
M54	-1.59	0.86	3.82	58.24	1.84	0.06	8.46	9.62	4.58	2.59	84.5	51.6	1.230	y	y	y	y
47Tuc	-0.76	0.52	3.65	56.11	2.03	0.09	7.96	9.48	4.81	1.50	68.8	38.0	1.000	n	n	n	(D)
NGC1851	-1.23	0.21	1.83	41.18	2.32	0.05	6.98	8.85	5.32	0.55	51.8	24.3	0.958	y	n	n	y
M79	-1.58	0.60	3.00	31.30	1.72	0.01	7.78	9.10	4.00	0.36	40.7	26.1	0.081	y	y	n	
M3	-1.57	1.66	3.39	115.54	1.84	0.04	8.84	9.35	3.51	0.96	37.2	22.7	0.115	y	n	n	(D)
M80	-1.77	0.44	1.89	38.63	1.95	0.00	7.73	8.86	4.76	0.50	48.7	28.1	0.592	y	y	n	
M13	-1.54	1.75	3.34	56.40	1.51	0.11	8.80	9.30	3.33	0.78	39.1	26.9	0.068	y	y	n	(D)
NGC6441	-0.53	0.37	2.18	27.23	1.85	0.02	7.77	9.19	5.25	1.57	102.0	62.0	2.364	y	y	n?	HB
M70	-1.52	0.08	2.44	20.71	2.50	0.01	5.62	8.83	5.41	0.18	39.3	17.3	0.183	y	y	n?	
NGC6752	-1.57	0.20	2.72	64.40	2.50	0.04	6.83	9.01	4.91	0.32	32.9	14.5	0.205	y	y	n	
M15	-2.27	0.21	3.18	64.42	2.50	0.05	7.02	9.35	5.38	1.19	62.1	27.4	1.168	y	n	n?	(D)
NGC7099	-2.12	0.14	2.68	42.68	2.50	0.01	6.38	8.95	5.04	0.24	34.1	15.0	0.160	y	n?	n	

Brown et al. 2001; Busso et al. 2004,2007; Conelly et al. 2004; D'Alessandro et al. 2008; D'Cruz et al. 2000; Dieball et al. 2007; Dieball et al. in prep.; Ferraro et al. 1998; Hill et al. 1996; Knigge et al. 2002; Landsman et al. 1996; Möhler et al. 1997, 2004, 2007; Mould et al. 1996; Parise et al. 1998; Ripepi et al. 2007; Rosenberg et al. 2004; Sandquist & Hess 2008; Watson et al. 1994; Zurek et al. in prep.

Results from KS tests:

	non-BHk vs. BHk	parent vs. Harris
M_{tot}	0.79	0.04
c	2.52	0.46
e	46.48	27.56
[Fe/H]	76.77	26.23
S(RR)	76.77	26.20
HBR	24.23	16.10
r_c	8.48	8.77
r_{hm}	10.19	42.58
r_{tidal}	70.72	4.89
$lg(t_c)$	8.48	40.22
$lg(t_{hm})$	10.19	18.59
$lg(\rho_c)$	20.05	1.12
v_c	20.05	0.04
v_{hm}	3.13	0.50
Γ	82.45	0.09

Correlation of cluster parameter and the presence of a BHk population: cluster mass



Results – so far:

- *5 BHk cluster*
- *11 non-BHk cluster*
- *KS test: most significant difference (> 99% confidence) in mass distribution:*

→ BHk clusters also amongst most massive GCs

→ high mass associated with BHk population

At first glance: supports He self-enrichment scenario

But what about selection effects?

- *Massive clusters contain more stars*

→ detection of rare BHk stars more likely

- *Low-mass GCs contain fewer stars*

→ no BHk stars, even if there is no physical lower mass limit for production of BHk stars

Is there a critical cluster mass limit for BHk production?

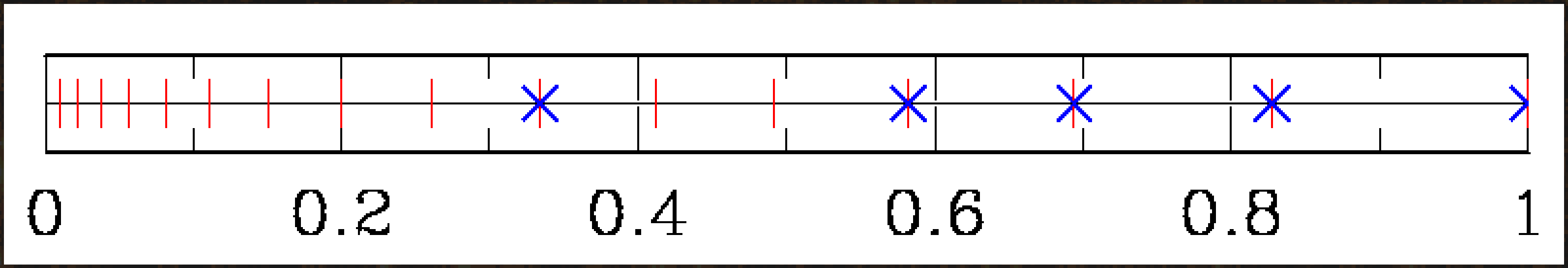
- *Location of BHk clusters in sorted, cumulative mass distribution of cluster sample*
- *Combine many low-mass clusters to form aggregate high-mass cluster*

→ *No mass limit: uniformly distributed*

→ *Mass limit: concentrated at high mass end*

(Verbunt & Hut 1987: connection between bright LMXBs and cluster collision rate)

Is there a critical cluster mass limit for BHk production?



KS-test : ≈ 40% probability that BHk clusters are randomly selected from uniform distribution

→ no statistically significant difference!

→ no evidence for a lower mass limit for clusters capable of producing BHk stars!

Discussion:

- *BHk populations have so far been found in high-mass clusters*
- *This does not (yet!) imply a lower mass cut-off*
- *Apparent preference for massive GCs might be because they also have more stars*

- *Whether or not there exists a lower mass-limit for BHk clusters: cluster mass is a key parameter*
- *However: high-mass clusters without BHk populations do exist! (47 Tuc, NGC 6441)*

→ *mass is not the only parameter associated with BHk stars*

Other parameters with significant differences:

	non-BHk vs. BHk	parent vs. Harris
M_{tot}	0.79	0.04
c	2.52	0.46
e	46.48	27.56
[Fe/H]	76.77	26.23
S(RR)	76.77	26.20
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$lg(\rho_c)$	20.05	1.12
v_c	20.05	0.04
v_{hm}	3.13	0.50
Γ	82.45	0.09

Caution: these parameters correlate also with mass!

Is binarity a key ingredient in producing BHk stars?

- Parameters might indicate decelaration of core collapse (most likely by presence of binaries)
- EHB binaries rare, but might still be binary product
- Binary interaction might enhance mass loss
  → production of late He-flashers (→ BHk stars)

BHk clusters and multiple populations:

- *Most BHk clusters also show multiple stellar populations (ω Cen, NGC 2808, M 54) and/or unusal HB (NGC 6388) → He self-enrichment*
- *However, so far no evidence for multiple populations in NGC 2419 (Sandquist & Hess 2008)*

- ***Present cluster sample does not allow conclusion of low-mass cut-off of BHk clusters***
- ***However: absence of evidence ≠ evidence of absence!***
- ***Lower mass limit might exist***
- ***Cluster sample biased towards high-mass clusters***

→ ***available cluster sample is too small & too deficient in low-mass clusters to allow a more definitive test of critical mass hypothesis***

Such a bias is to be expected: high mass clusters are usually the more promising targets for both physical and observational reasons

Summary

- *BHk stars rare*
- *Found in only few, massive GCs*
- *However, present cluster sample does not (yet) allow conclusion of low-mass limit*
- *Most (but not all) BHk clusters also have multiple populations*

But:

- *not all clusters with multiple populations have BHk population (NGC 6441, NGC 1851)*
- *Not all massive clusters have BHk population (47 Tuc, NGC 6441)*

Mass seems to be the main, but not the only parameter relevant for existence of a BHk population in a cluster

How to improve?

- *Clearly need more GCs in which reliable BHk identification is possible*
- *More low-mass GCs*
- *Number of BHk stars ↔ total cluster mass*

cluster	BHB	EHB	BHk	mp	#BHk
NGC2419	y	y	y		$\gtrsim 190$
NGC2808	y	y	y	y	$\gtrsim 50$
ωCen	y	y	y	y	$\gtrsim 25$
NGC6388	y	y	y	HB	$\gtrsim 10$
M54	y	y	y	y	$\gtrsim 30$
47Tuc	n	n	n	(D)	
NGC1851	y	n	n	y	
M79	y	y	n		
M3	y	n	n	(D)	
M80	y	y	n		1?
M13	y	y	n	(D)	
NGC6441	y	y	n?	HB	4?
M70	y	y	n?		1?
NGC6752	y	y	n		
M15	y	n	n?	(D)	1
NGC7099	y	n?	n		

Dieball et al. 2009, MNRAS accepted

Today on astro-ph: 0901.1309