STAR CLUSTERS AS TOUCHSTONES FOR THEORIES OF GALACTIC EVOLUTION - A FEW EXAMPLES

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ABSTRACT

Observations of NGC 5128 (Cen A) show that this giant elliptical galaxy contains few globular clusters. The fact that the number of globular clusters per unit luminosity in E galaxies has a range of $\sim 10^2$ indicates that different ellipticals were formed in differing physical environments. It is pointed out that more data on the frequency with which globular clusters occur in elliptical galaxies might place interesting constraints on theories of galaxy clustering.

Intercomparison of the Local Group galaxies IC 1613 and the SMC shows that differences in the frequency of cluster formation also occur among Irregular galaxies.

It is pointed out that globular clusters associated with distant galaxies probably start to outnumber galactic stars for $B > 31$.

The discovery that the LMC supernova remnant N63A is situated in the small association N2030 shows that this object must have been formed from a star with a main sequence mass $> 30\ M_{\odot}$.

Finally we show that E3, which is one of the faintest known galactic globular cluster, was decimated by tidal forces. Due to the interplay of equipartition and tidal effects this cluster has been severely depleted in single stars while retaining many (presumably binary) blue stragglers.

1. INTRODUCTION

One of the dangers associated with living on a beautiful isle, such as Vancouver Island, is that it is very easy to become insular By the same token it is all too easy for us, working in various exciting areas of cluster studies, to forget about the broader impact that such work might have on other areas of astronomy. The justification of our work on clusters is not just that it is fun but also

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that such investigations often help to illuminate other branches of science. In what follows I should like to give a few examples, drawn from my own recent work, of cluster research that might hopefully be of some interest to workers in other fields.

2. DOES NGC 5128 CONTAIN GLOBULARS?

A plate of this galaxy, which has an estimated limiting magnitude $B \sim 22.7$, was obtained at the prime focus of the CTIO 4-m telescope. The search for globular clusters on this plate is rendered difficult by the following factors:

a) At a distance of ~ 3 (100/H)Mpc globular clusters appear stellar.

b) Because NGC 5128 is situated at a low galactic latitude ($b = +19°$) our plate has a high surface density of faint foreground stars.

c) Active star formation along the edges of the dust band crossing the face of this galaxy makes it impossible to recognize clusters in the equatorial region of NGC 5128.

d) The difference in surface density between the background and the main body of this galaxy makes it difficult to count star-like images to the same magnitude limit over the entire plate.

The last two difficulties were largely overcome by (1) constructing a "sandwich" consisting of the original (negative) plate and a slightly out of focus contact positive and (2) by counting only stars in the polar regions of NGC 5128. The results of these counts of star-like objects are given in Table 1. The counted area, which comprises that $\sim 1/3$ of NGC 5128 which is free of star formation and dense absorption, contains an excess of 5 ± 20 m.e. images. The total number of clusters brighter than $B \sim 22.7$ is therefore $\simeq 15 \pm 60$. Assuming the globular clusters in NGC 5128 to have the same luminosity function as that of globulars in the Local Group it is found that the total number of clusters (including those below the plate limit) is ~ 20 for $H = 50$ km $s^{-1}Mpc^{-1}$ and ~ 15 for $H = 100$ km $s^{-1}Mpc^{-1}$. This compares with a total cluster population $\gtrsim 3000$ that would be expected <u>if</u> NGC 5128 had the same number of globular clusters per unit luminosity as does M87.

Why is M87 so rich in globulars whereas NGC 5128 appears so cluster-poor? A definitive answer to this question will not emerge until more information is available on the frequency of globular clusters per unit luminosity in a large sample of elliptical galaxies in different environments. Lacking such data one might speculate that M87 is cluster-rich because it is situated near the centre of the Virgo cluster whereas NGC 5128 might be cluster-poor because it is a field galaxy. If this working hypothesis is correct then cluster and field

TABLE 1

COMPARISON OF OBSERVED AND PREDICTED
COUNTS* IN NGC 5128

Rings†	3-5	6-10	11-15	3-15
Observed	32	98	144	274
Predicted‡	27±1	92±4	150±7	269±12
Excess	+5	+6	-6	+5

* Counts refer only to the polar zones with position angles 0° - 60° and 180° - 240°.

† Ring n extends from 18.2(n-1/2) to 18.2(n+1/2) arcsec from the galaxy nucleus.

‡ From background counts in rings 16 - 25.

galaxies of the same type might have been different ever since the era of proto-galactic collapse. This would conflict with the presently popular notion that giant clusters form as a result of gravitational interactions between pre-existing galaxies.

3. STAR CLUSTERS IN IC 1613 AND THE SMC

In his book Evolution of Stars and Galaxies Walter Baade draws attention to the fact that the Local Group dwarf IC 1613 contains few, if any, star clusters. In this respect it differs drastically from the Small Magellanic Cloud. To check if this apparent difference might be due to the fact that the SMC is nearer to us than IC 1613 I have intercompared a Curtis Schmidt plate of the Small Cloud with a similarly exposed plate of IC 1613 taken at the prime focus of the 5-m Hale telescope. In order to make this comparison (see Table 2) even more precise a copy of the SMC plate was defocussed so that the stellar images had a diameter of ∿ 13" (corresponding to ∿ 1" at the distance of IC 1613). This comparison shows that > 15 clusters are visible in the SMC whereas none can be seen in IC 1613. On the basis of these results, which are discussed in detail in Astrophys. J. **230**, 95, 1979, it is concluded that star forming regions in the Small Cloud are presently more prone to forming star clusters than are similarly active regions of star formation in IC 1613. The reason for this peculiar difference in behaviour is not presently understood.

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TABLE 2

COMPARISON BETWEEN THE SMALL MAGELLANIC CLOUD AND IC 1613

Galaxy	Type	M_V	D(Kpc)	No. Bright Clusters
SMC	Ir IV/IV-V	-16.6	58	>15
IC 1613	Ir IV	-15.1	760	0

4. GLOBULAR CLUSTERS AND THE SPACE TELESCOPE

Most luminous galaxies are embedded in huge halos of globular clusters. Globulars that project beyond the main body of their parent galaxies will be counted as stars in deep log N(B) versus B ("count-brightness") surveys. The combined galaxy and globular cluster luminosity functions, normalized under the assumption that a galaxy of M_B = -20 contains 100 globulars, is given in Fig. 1.

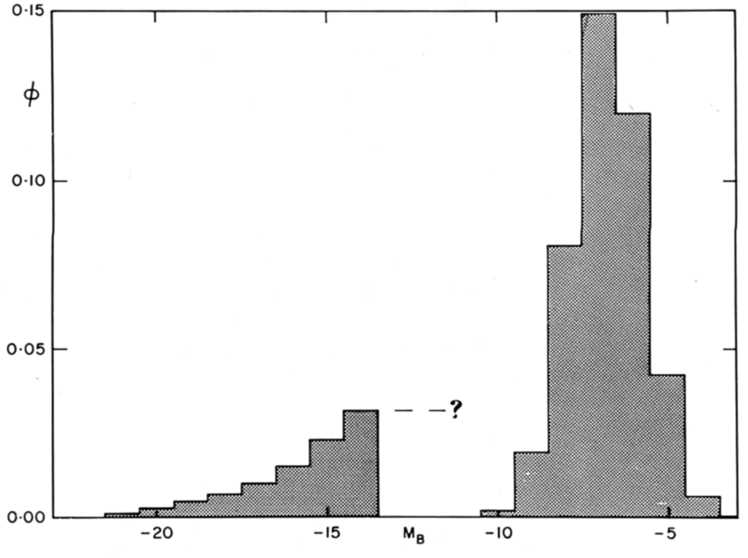

Figure 1. Luminosity function for globular clusters (right) and galaxies (left).

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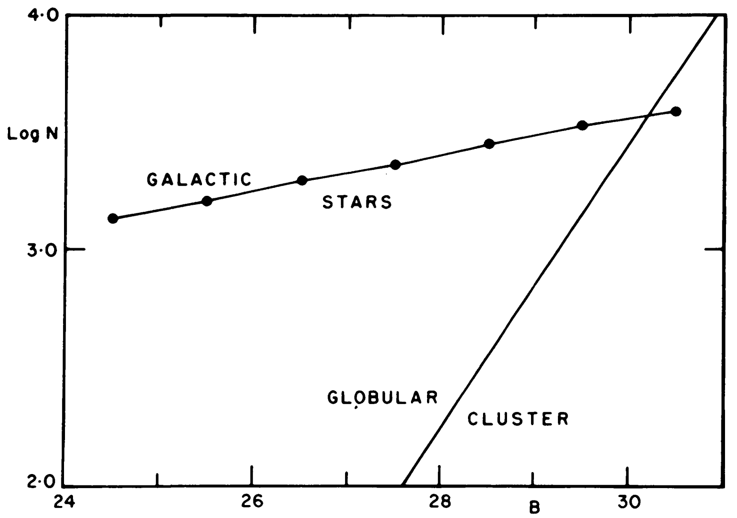

Figure 2. Comparison of predicted counts of faint stars and globular clusters at b = ±90°.

Since the space density of parent galaxies is roughly constant out to distances of a few hundreds of Mpc the count-brightness relation for globular clusters associated with them will have a slope $\sim$ 0.6. This is much steeper than that expected for galactic halo stars which have a space density that drops rapidly with increasing Z. As a result globulars will give a non-negligible contribution to N(B) for B > 25, and dominate the counts for B > 31. A detailed comparison between log N(B) for clusters and halo stars is given in Fig. 2. The data for halo stars are based on a recent unpublished model by Pritchet and van den Bergh. The extrapolation of the cluster counts to B = 31 is of more than academic interest because such information is needed to do photometry of objects having B = 25 with an accuracy of 1%.

5. THE SUPERNOVA REMNANT N63A

Most of the massive stars in X-ray binaries have probably undergone significant amounts of mass exchange and mass loss. Such systems are therefore of little value in attempts to estimate the original masses of the stars that formed the compact objects which these binaries now contain. A much more favourable situation would arise if a supernova remnant could be found in a cluster or association which, presumably, consists of coeval members. At the present time the only known example of such an objects is N63A, which is situated in the

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small LMC association NGC 2030. From UBV photometry of the brightest members of this association van den Bergh and Dufour find that the most highly evolved association member presently has M_{bol} = -9.0 and log T_{eff} = 4.5. Evolutionary calculations with conservative mass-loss estimates yield an original main sequence mass $\sim$ 30 $M_{\odot}$ for this star. It follows that the supernova which produced N63A must have had an initial mass > 30 $M_{\odot}$.

6. THE GLOBULAR CLUSTER E3

New deep sky surveys carried out with the UK Schmidt telescope in Australia and the ESO Schmidt in Chile have resulted in the discovery of a number of new faint star clusters. The first of these which has been studied in detail is E3 located at α = $09^h\ 21^m6$, δ = -77°04' (Epoch 1950). A colour-magnitude diagram of this cluster (see Figure 3) has recently been obtained by van den Bergh, Demers and Kunkel. The CM diagram of the cluster, which is located at a distance of $\sim$ 8 Kpc, shows a well developed main sequence plus a significant number of "blue stragglers" and very few red giants. A comparison field CM diagram shows that these blue stragglers are, in fact, cluster members. The absolute magnitude of E3 turns out to be M_V = -4.2, which makes this one of the faintest globulars so far discovered in the Galaxy. The low luminosity of this cluster may be understood if it is assumed that this

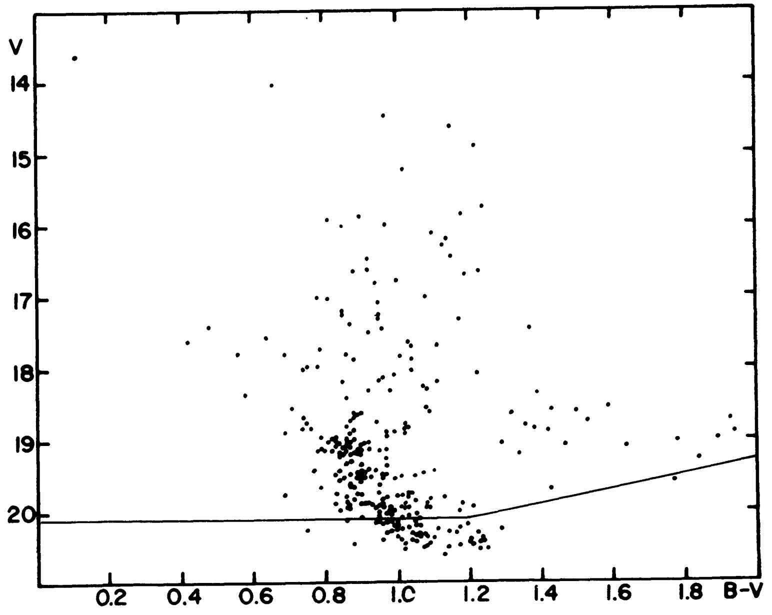

Figure 3. Color-magnitude diagram of the dying globular cluster E3 is dominated by (presumably binary) blue stragglers.

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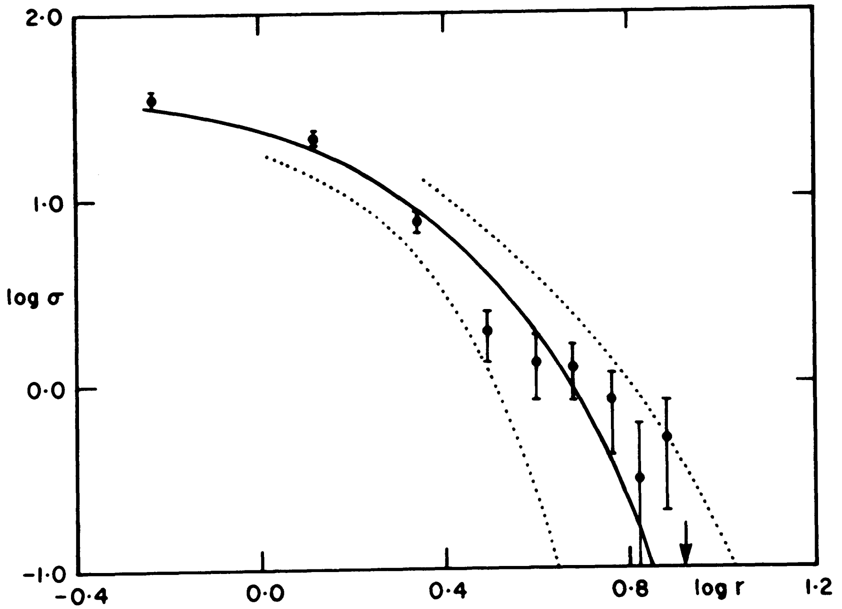

Figure 4. Radial density profile of E3. This cluster exhibits one of the smallest known values of r_t/r_c.

cluster has suffered severe tidal damage. Star counts (see Figure 4) show that E3 has a core radius r_c = 4.4 pc and a tidal radius r_t = 26.4:pc. The resulting value of r_t/r_c is among the smallest for any globular that has so far been studied. Equipartition of energy will lead to a concentration of (presumably binary) blue stragglers to the cluster core where they will be less depleted by tidal effects than the single stars in the cluster halo. This may account for the relatively large number of such objects in this cluster.

The core radius of E3 is similar to that of the "Palomar type" clusters that normally inhabit the galactic halo. The fact that E3 presently has $\tilde{\omega} \sim 9$ kpc and Z = -2.6 kpc suggests that it is now close to perigalacticon. This conclusion is consistent with the presently observed value of the tidal radius for this cluster.

In summary it appears that E3 is the first known example of a globular cluster that is rapidly approaching death by, and disintegration resulting, from external tidal forces.

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Striking confirmation of the conclusion that tidal forces can and do remove stars from globular clusters is provided by the observation that galactic globular clusters with small r_t/r_c values have a $\sim$ 5 times lower mean luminosity than do those with large r_t/r_c. For 51 clusters with $\log(r_t/r_c) \geq 1.25$ it is found that $\langle M_V \rangle = -7.96 \pm 0.13$ compared to $\langle M_V \rangle = -6.19 \pm 0.24$ (m.e.) for 11 clusters with $\log(r_t/r_c) \leq 1.00$.

Detailed literature references will be given in the individual research papers on which this contribution is based. The data on numbers of globular clusters expected down to B $\sim$ 31 are to be published in the proceedings of IAU Colloquium No. 54. The work on E3 has been submitted for publication by van den Bergh, Demers, and Kunkel. That on N63A will be published by van den Bergh and Dufour.

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DISCUSSION

BOK: Who wishes to open the discussion? Well, I'll open it. How do you separate the red globulars from the blue globulars? When you get to your elliptical galaxies is there a good fraction of them that are possibly blue globulars? After all, in the Magellanic Clouds there are quite a few of them.

VAN DEN BERGH: Well, I think I prefer to follow the nomenclature suggested by Paul Hodge who refers to the blue objects in the Magellanic Clouds as "young, populous clusters" rather than "blue globular clusters".

BOK: Yes.

VAN DEN BERGH: In the case of the giant elliptical galaxies such as M87, of course, the evidence we have is that all of these objects are, in fact, red globulars. In the case of NGC 5128 there are, in fact, 11 objects which are somewhat fuzzy in outline, and which are blue, which are located within the dark absorbing band. These are probably open clusters or small associations.

BOK: I have committed the cardinal sin by not mentioning my name. My name is BOK, spelled "B" "O" "K"!

CAYREL: What kind of stars are those in your globular cluster, E3, on the right hand, which are not on the main sequence, but above the main sequence? They cannot be pre-main-sequence stars because this globular cluster is so old. They are least a magnitude above the main sequence.

VAN DEN BERGH: Yes, so presumably they are blue stragglers and there are theoretical reasons for believing that blue stragglers are binary stars. This was a point reviewed by Professor Paczynski in his talk in Montreal last week. Although there is still no firm evidence that blue stragglers are binaries, it seems according to him, the "best buy" theory at the present time. I must add that one of the blue stragglers is very similar to the star V29 in the cluster M13. It has an absolute magnitude of about -2.

BOK: I see three distinguished hands going up.

WALLERSTEIN: I should mention a preprint by Craig Wheeler. He thinks the blue stragglers, in fact, are not binaries, but are stars which have delayed evolution up from the main sequence. One of the main reasons for this is that there is not a single orbit for a so-called blue-straggler in a galactic cluster.

CANNON: Why do you describe E3 as a globular cluster rather than an old open cluster?

VAN DEN BERGH: There are two reasons for this. In the first place it is rather far above the galactic plane for an open cluster. In the second place, the distance between the main sequence turnoff and the vertical giant branch differs significantly from the value observed in any open cluster and is very similar to the values found in the globulars.

CANNON: But, if I remember your diagram correctly, the turnoff is coming in at about 19, which is not very distant for a true globular cluster. There is no evidence for a horizontal branch . . .

VAN DEN BERGH: Yes.

CANNON: And I would have thought that it looks at first glance, and I would like to see more of it later, much more like NGC 188, which also has a very large population of both blue stragglers and red giants.

VAN DEN BERGH: We have compared the distance from the vertical giant branch to the main sequence turnoff in this cluster and in M67, and the separation is much more like that in a globular than that in an open cluster.

HAWARDEN: I would like to support Russell in that it seems to me that there isn't any evidence for a well-defined vertical giant branch at all. You have a sort of mess of stars above the main sequence and the Hertzsprung gap, and otherwise the main sequence and the sequence of unevolved blue stragglers looks exactly like any reasonably well populated older cluster.

HANES: I'd like to go back to this business about the total number of globulars associated with the galaxy. You say that Racine has found evidence that M87 contains about 8,000 clusters. But those kinds of calculations come from the work of Harris, which extends out to very large distances, about 30 arcmin in fact; whereas in NGC 5128, you're differencing annuli at much smaller physical scales, since it's so much closer. So what you difference is not globulars vs. sky, but an excess of globulars vs. globulars themselves, and simple scalings don't work. If M87 were at the distance of NGC 5128 you're only going to be seeing some fraction of the globular clusters, and the differencing is not going to give you the correct value for the total population. So have you considered what kind or portion of the globular cluster system you are actually sampling?

VAN DEN BERGH: Yes. The surface density of globular clusters, of unresolved objects, is just totally flat out to as far as you can see, which is not the case for M87.

FREEMAN: Just going back to this question of the blue stragglers again. If you look at the other clusters of low concentration, are there more blue stragglers in those per unit giant than in the more concentrated ones?

VAN DEN BERGH: I don't know what the answer to that is.

HARDY: Going back again to the indication of the age of E3, I don't think you have enough stars at the upper end of the giant branch to really make a comparison with an evolutionary sequence. If we look at the blue stragglers, at the general shape of the giant branch, and at the position and shape of the main sequence, I would suggest that the cluster looked exactly like NGC 7789 or NGC 2158 in the Galaxy, which also have a larger quantity of blue stragglers. So, I am not at all sure about the identification of the cluster as a globular. I understand that you cannot use the horizontal branch as a clue, because of the scarcely populated giant branch. Do you have any other reasons to believe it is a globular cluster?

VAN DEN BERGH: No, I think that the two main arguments are the ones that I gave, one about the separation of the vertical giant branch and the turnoff, and the other the large distance from the galactic plane.

HARRIS,W.: Returning to the comparison between M87 and NGC 5128, you pointed out those two cases as being perhaps extreme examples of total numbers of globular clusters. But if you include the totality of all the elliptical galaxies that we know about at the present time that have globular cluster populations, then I think one shouldn't forget that it is possible to define a normal relation, or a normal proportionality, between luminosity and number of clusters . It is satisfied by most of the galaxies in the Virgo system, as Dave Hanes would point out, I think, and by the ones in the local group. Perhaps the situation is not quite as chaotic as you have indicated, in that there is a normal relation to which these anomalies can be compared.

VAN DEN BERGH: Perhaps one could say the following: that it looks as if there are three regimes. One is M87, which is in the center of a rich cluster; next are members of clusters, which applies to the Virgo cluster and some members of the local group; and, finally, isolated field galaxies; and as long as you have one galaxy per box then this description seems adequate. (Laughter).

HARRIS, W.: Hopefully that situation will approve.

VAN DEN BERGH: But it certainly will be very important, I think, to look at additional elliptical galaxies located in widely differing environments.

CARNEY: Regarding the supernova progenitor for N63A, it seems to me your mass estimate depends upon the existence of one star; how certain are you that one star is affiliated with N63A?

VAN DEN BERGH: Well, it's a well defined association and this is . . .

CARNEY: But one star is well above all the rest and could be a foreground star.

VAN DEN BERGH: If you were to take the next star down you would probably be down to $20M_{\odot}$.

RACINE: NGC 5128 again. It is well known that this is a highly peculiar galaxy: either it is exploding, or it is colliding, or it is doing something; and I think we should be rather careful drawing conclusions from that one case. It may well be that the globular cluster system itself may be highly peculiar.

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VAN DEN BERGH: Of course, one has to remember that not only is 5128 exploding, but M87 is exploding, as well.

KING: I don't need to say my name, because Bart is going to say it again afterwards, but my name is Ivan King. A comment on your field stars and globular clusters as seen by the Space Telescope. I think that this is not really a problem, because the globular clusters that you counted are going to be in concentrations around clearly visible galaxies. They are not going to be widely and uniformly scattered like the field stars.

VAN DEN BERGH: This is certainly true, although the distribution of galaxies is sufficiently patchy that, say, in areas like the Virgo cluster, one is probably already running into this problem at 25th magnitude. A large fraction of the stellar images that you see may, in fact, be globular clusters.

BOK: Thank you very much Dr. Van den Bergh; the next speaker on the program is Gosta Lyngå, and Dr. Lyngå will speak on Clusters, Associations and Galactic Structure and he will speak for 39 and ½ minutes. (Laughter).