THE OLDER CLUSTERS IN THE MAGELLANIC CLOUDS

S.C.B. Gascoigne
Mount Stromlo and Siding Spring Observatories
Research School of Physical Sciences
Australian National University, Canberra.

We begin with Fig. 1, which somewhat aged though it may be still illustrates important aspects of the subject (Gascoigne 1971)

(i) There is a clear division of cloud clusters into a blue and red group. The division corresponds to the mass around $2.5M_{\odot}$, at which core degeneracy first develops in stars approaching the giant branch. Such stars spend about three times as long on the giant branch and travel higher up it than the slightly heavier non-degenerate stars, and so dominate the colours of the clusters in which they occur.

(ii) The red clusters are somewhat less luminous than the globular clusters in the galaxy. Freeman and Chun (1972) have shown from dynamic arguments that the cloud clusters are also less massive, by enough to keep the M/L ratios roughly the same as those in the galaxy.

(iii) For a long time it has been taken that the blue clusters are young and the red clusters old. Thus the clouds present us with a truly two-parameter family of globular-like clusters, the parameters being of course age and abundance.

Earlier work, mostly on C-M diagrams, pointed to three general classes of old cloud clusters:

(i) regular globular clusters, complete with RR Lyraes and horizontal branches; and (ii) and (iii), types peculiar to the SMC and LMC respectively, which had no galactic counterparts, presumably because they represented combinations of age and abundance not yet encountered in the galaxy. In these clusters very red giants, well beyond the tips of the normal giant branches, were common; some at least were shown by Feast and Lloyd Evans (1973) to be carbon stars. Another unexpected result was provided by the integrated colours of van den Bergh and Hagen (1968), which when plotted in the (U-B), (B-V) plane did not lie along a line as Racine had found for galactic

James E. Hesser (ed.), Star Clusters, 305–315.

https://doi.org/10.1017/S0074180900092044 Published online by Cambridge University Press

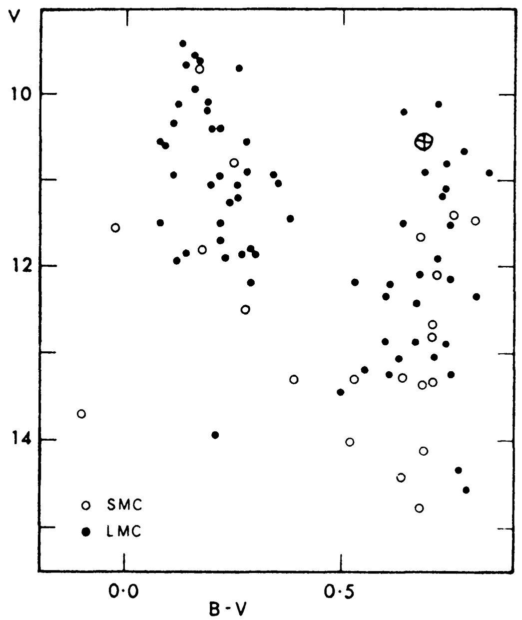


Fig. 1 Integrated magnitudes and colours for Magellanic Cloud clusters. No reddening corrections have been made. + indicates an average halo cluster seen at the distance of the Clouds.

globulars, but scattered over an appreciable area. Finally integrated magnitudes measured by Danziger (1973) in a number of intermediate width wavebands, including the DDO bands, indicated that substantial abundance differences occurred among the Cloud clusters.

The advent of the new large telescopes in the south has stimulated the subject tremendously, and led to the formulation of many new programmes. Ours at Mt. Stromlo is aimed at measuring ages and abundances for some of the old Cloud clusters and so of learning something about the early evolutionary history of the Clouds. Ages are found from C-M diagrams and abundances from the spectrophotometry of individual giants, though because of the faintness of the stars involved the observational difficulties can be formidable, even with the AAT.

To illustrate the practicabilities, Fig. 2 shows how the magnitude at turnoff is related to age and composition. The turnoff luminosities are taken from the compilation of Ciardullo and Demarque (1977), and shown in the figure as they would appear at the

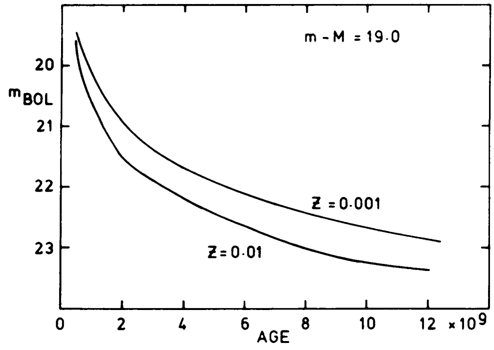


Fig. 2 Age against magnitude at turnoff point for a cluster with the modulus of the SMC (19.0).

distance of the SMC, the modulus for which has been taken as 19.0. A knowledge of the modulus is clearly essential in that it eliminates the need for main sequence fitting and so makes the programme practicable. Even so for older clusters we must go fainter than V = 22, and must as well have a reasonable idea of the abundances.

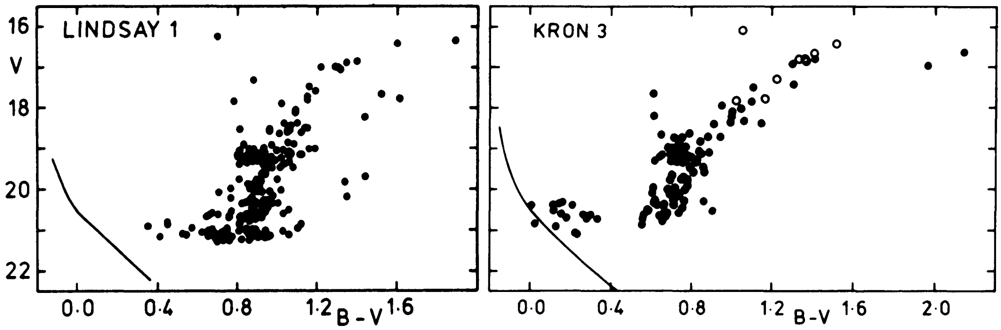
C-M diagrams, based on data obtained mostly with the AAT and the CTIO 4-metre telescopes are shown in Figs. 3 and 4 for the SMC clusters Lindsay 1 and Kron 3. At first sight Lin 1 is like 47 Tuc (Lee 1977); but colour for colour its giant branch is more than half a magnitude brighter, there is no obvious AGB, and there is no gap between the horizontal and giant branches as in 47 Tuc. On current estimates (Table 1, Pilachowski (this volume)), the abundances are about -1.5 for Lin 1 and -1.1 for 47 Tuc. Whether the blue stars at V = 21 comes from a main sequence turnoff is still uncertain: all we can say at present is that Lin 1 cannot be younger than about 4×10^9yr.

Brighter than V = 20 Lin 1 and Kron 3 are very similar, except that the clump or horizontal branch in Kron 3 is a little bluer. But the Kron 3 diagram shows the upper end of a main sequence at V $\sim$ 20.5, indicating an age of perhaps 3×10^9yr, so that, as has been surmised for some time, it is indeed an intermediate age cluster.

C-M diagrams going fainter than V = 20 have also been measured for NGC 1868 (Flower et al, 1979), NGC 2209 (Gascoigne et al, 1976), NGC 2231 (Walker 1979b), Hodge 11 (Walker 1979a; Freeman and Gascoigne 1977), and NGC 2257 (Gascoigne, unpublished). NGC 1868, 2209 and 2231 were selected to some extent as the bluer clusters of the red group; they are quite alike, with similar ages and abundances. There is general agreement that Hodge 11 is *extremely* metal-poor but while Freeman and Gascoigne put it among the globular clusters, Walker

https://doi.org/10.1017/S0074180900092044 Published online by Cambridge University Press

think it is more like the Hyades in age. This point, which is important in other contexts, can perhaps be best settled by deciding which features of the C-M diagram belong to the cluster and which to the background.



Figs.3,4 Colour-magnitude diagrams for the SMC clusters Lindsay 1 and Kron 3.

Initially we measured abundances by broad-band Canterna photometry of individual giants, and showed that in spite of their probable age differences (see Table 1) the three SMC clusters NGC 121, Lin 1 and Kron 3 all had an [Fe/H] of about -1.5 (Bessell, 1980). It has however proved more efficient to use spectrophotometry. Spectra of individual stars in the range λ3700 - λ6300 were obtained on the AAT with the Boksenberg detector, and the resulting intensity curves folded with the DDO response curves, the DDO system having been chosen because it is well calibrated and well understood. The transformations were checked with DDO stars in 47 Tuc, NGC 2243 and NGC 6752.

In all 34 stars were observed. Plots of the 38-45 index against the 45-48 index are shown in Fig. 5. The nomenclature and general procedure follow Hesser, Hartwick and McClure (1977). From their anomalous positions in the Figure and from the strengths of their λ5100 M_gH bands it was inferred that six were foreground sub-dwarfs, while W46 and W50, two very red stars in NGC 2209, were found (as many people have now done) to be carbon stars. The results are summarised in the DDO column in Table 1.

https://doi.org/10.1017/S0074180900092044 Published online by Cambridge University Press

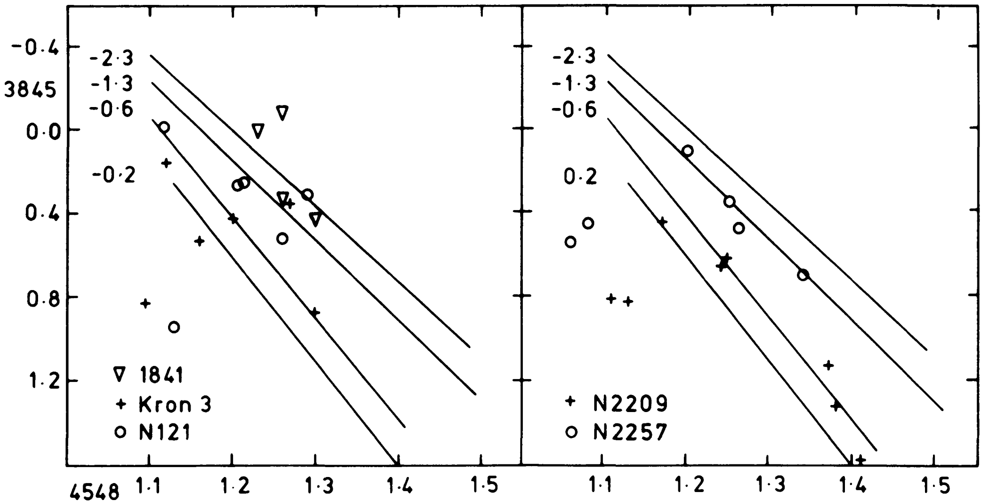


Fig. 5 DDO observations for giants in some Cloud clusters. For corresponding data for clusters in the galaxy see Hesser, Hartwick and McClure (1977).

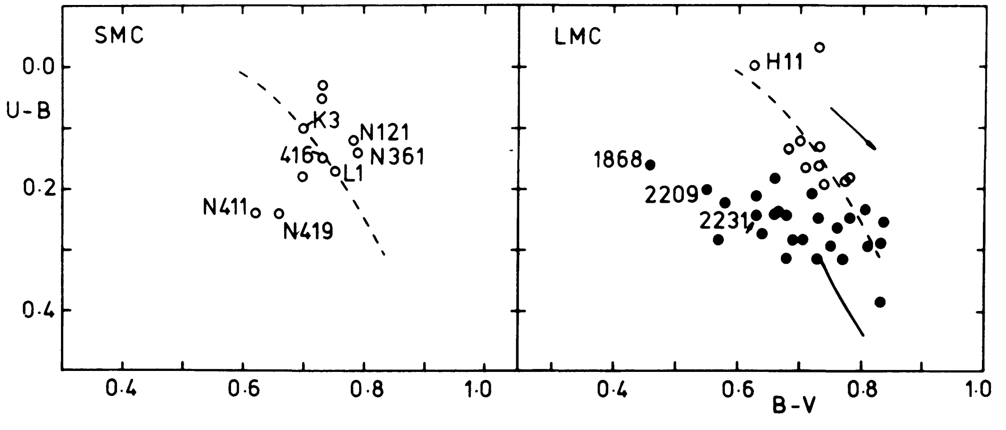
Hartwick and Cowley (1978) have been working on similar lines, with emphasis on the possibility of a disk-halo structure for the clusters in the LMC. They use three criteria to distinguish between the two groups: integrated UBV colours, C-M diagram morphology, with emphasis on the presence of blue (halo) or red (disk) horizontal branches, and abundances measured from line strengths in the spectra of individual giants. They have also made an abundance calibration for Danziger's intermediate band colours, a calibration we reproduce in Table 1. Two comments may be added to their own discussion. The UBV colours are plotted separately for the two clouds in Figs. 6 and 7. Hartwick and Cowley's suggestion was that bluer than U-B $\simeq$ 0.2 the clusters belonged to the halo group; redder, their ages may extend up to the 8 x 10^8 years of N2209 and they were disk clusters. As far as it goes this is borne out by recent work in the LMC, but in the SMC Kron 3 falls right on the Racine line and has in fact identical colours with ω Cen, which of course it resembles not at all. Note also the position of Hodge 11 in Fig. 7. The second comment is that the numerous spectra of cluster giants now existing should in time yield radial velocities, and so solve the long-standing problem of determining reliable velocities for the Cloud clusters.

https://doi.org/10.1017/S0074180900092044 Published online by Cambridge University Press

Table 1

	Ages $\times 10^9$ yrs	Broad-band	[Fe/H] DDO	Danziger
SMC				
Lin 1	8 ?	-1.5		-1.0
Kron 3	3	-1.5	-0.6	-1.4
NGC 121	12	-1.5	-1.1	-1.4
LMC				
NGC 1466	12			-1.4
1841	12		-2.4	-2.0
1868	0.7	-1.3		
2209	0.8	-1.2	-0.6	
2231	1.3	-0.9		-2.3
2257	12	-1.3	-1.3	
Hodge 11	0.6 12	-2.5		-2.0

The ages of the globular clusters have been taken at a conventional 12×10^9 years. The broad-band abundances for the SMC clusters are from Canterna photometry, the LMC clusters from C-M diagram morphology. From estimates of individual spectral features, Hartwick and Cowley (1978) quote -2.0 for NGC 1841, and -1.6 for NGC 2257.



Figs.6,7 Integrated UBV observations for Cloud clusters. The dashed line is the intrinsic relation found for galactic globular clusters by Racine.

https://doi.org/10.1017/S0074180900092044 Published online by Cambridge University Press

At this stage only a bold man would predict any general result from the ages and abundances in Table 1; one may remark though that while abundance determination now seems under control, in that there are several practicable methods available, the same cannot be said for age determination. Two other criteria come to mind. One may reasonably attribute an age of at least 10^{10} years to any cluster containing RR Lyraes. And the presence of carbon and CH stars is usually taken as indicating intermediate age: certainly very red carbon stars do not occur in galactic globular clusters. Mould and Aaronson (1979) have recently attempted to put this idea on a more quantitative footing. They argue that stars need a certain minimum mass before they can move beyond the asymptotic giant branch into the carbon star region, and that if they have so much mass they must be younger than the statutory 10^{10} years. But Frogel and Persson have weakened this result by concluding from direct infrared measurements that Mould and Aaronson overestimated their bolometric corrections and hence their masses. (Frogel gave a brief description of this work in a part of the discussion which has been lost)*. Nevertheless these very red stars must have something to tell us.

Another attack on the problem has been made by Searle (unpublished; for an account of an earlier stage see Bagnuolo 1976). Searle measured the integrated colours of many Cloud clusters through four broad-band filters, designated u,v,g, and r, and centred at 3545, 3970, 4930 and 5975A respectively. Note that u and v are like two halves of the Johnson U; v is a heavily blanketed region, while u falls immediately below the Balmer discontinuity. From these filters Searle formed two reddening-free combinations Qugr and Qvgr, analagous to Q(UBV). In Fig. 8 I plot some data kindly supplied by Searle (a preliminary version is available in Bagnuolo). The clusters indicated are mostly from Table 1. There is an obvious overall run with age, from the upper left down to globular clusters like Hodge 11 and NGC 1466, 1841 and 2257 at the other, enclosed end. A number of galactic globulars are also indicated. It appears unlikely that the Clouds contain any old, relatively metal-rich clusters like 47 Tuc and NGC 6838.

I thank the many people who have sent me preprints and other advanced communications of their results.

*(See P. 321 - Ed.)

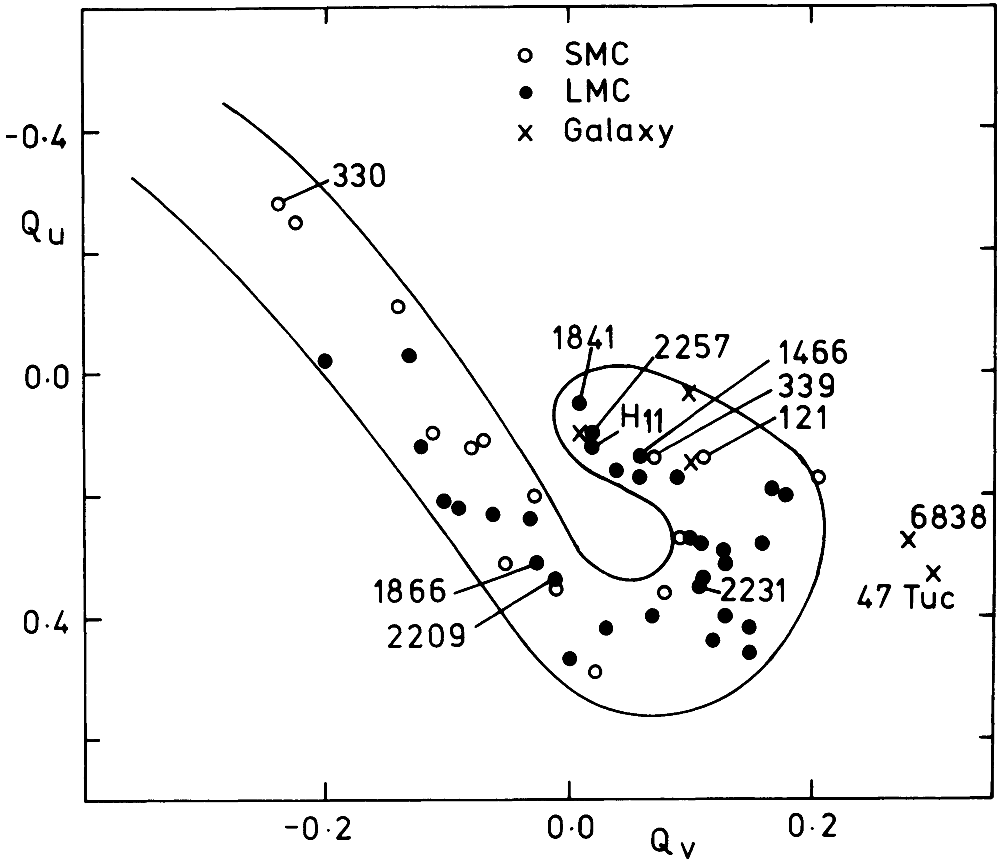


Fig. 8 Qu and Qv as measured for some Cloud clusters (see text for explanation) by Searle and Bagnuolo.

REFERENCES

Bagnuolo, W., 1976 Thesis: University Microfilms International

Bessell, M.S., et al. (1980) in preparation

van den Bergh, S. and Hagen, G.L., 1968, *A.J.* 73, 569.

Ciardullo, R.B. and Demarque, P. 1977, Trans. Yale Univ. Observatory 33, 34, 35.

Danziger, I.J., 1973, *Ap.J.* 181, 641.

Feast, M.W. and Lloyd Evans, T., 1973, *MNRAS* 164, 15P.

Flower, P.J., Geisler, D., Hodge, P. and Olszewski, E., 1979, *ApJ* in press.

https://doi.org/10.1017/S0074180900092044 Published online by Cambridge University Press

Freeman, K.C. and Chun, M. 1972 *Proc. A.S.A.* 2, 151.
Freeman, K.C. and Gascoigne, S.C.B., 1977 *Proc. A.S.A.* 3, 136.
Gascoigne, S.C.B. 1971 *The Magellanic Clouds* D. Reidel, p.25.
Gascoigne, S.C.B., Norris, J., Bessell, M.S., Hyland, A.R. and Visvanathan, N., 1976, *Ap.J.* 209, L25.
*Hartwick, F.D.A. and Cowley, A.P. 1978, Nato Advanced Study Institute on Globular Clusters, Cambridge England 1978.
Hesser, J.E., Hartwick, F.D.A. and McClure, R.D. 1977, *Ap.J. Suppl.* 33, 471.
Lee, See-Woo 1977, *A & A Supp.* 27, 387.
Mould, J. and Aaronson, M. 1979, *Ap.J. in press*
Walker, M.F. 1979a, *MN* 186, 767.
1979b, *MN* 188, 735.

*The paper referred to appears on page 433 of this volume - Ed.

https://doi.org/10.1017/S0074180900092044 Published online by Cambridge University Press

DISCUSSION

WALLERSTEIN: I'm very pleased to notice that Searle seems now to recognize the value of the Washington system of photometry for the study of globular clusters, because this new system seems to imitate very closely the C,M and T_1 colours of the Washington system.

GASCOIGNE: Searle's filters were based on Gunn's and were used in 1973 (see Bagnuolo's thesis). Both systems utilise the relative freedom of the redder end of the spectrum from line blocking, but it seems to me the emphasis is different: on the UV in Searle's case, and on the red and near infra-red in Canterna's.

COHEN: I just wanted to say that Searle did that several years ago and the system was defined even before them. I think some of those observations are four and five years old.

GASCOIGNE: Yes, that's true. I'd better make this clear: it works and it is really useful.

HARDY: I think that the colour-colour method of Searle can provide ages and metallicities. Do you remember the value of age and metallicity of NGC 416 on that diagram?

GASCOIGNE: Well, no. In fact, Searle's numbers haven't been calibrated. No one has an age for 416. Judging from Arp's CM diagram it could be, at youngest, like Kron 3. It is of course a difficult object, in the most crowded part of the SMC.

HARDY: In praise of the Washington system, I did reobserve the same stars you observed in the DDO system in NGC 2209 by using the Washington system I found -0.6, which seems to agree well with the DDO results. It's very easy to use the Washington system, especially for the Clouds, because it's so efficient photonwise.

GASCOIGNE: Oh, sure.

HARDY: Also, from integrated photometry on the Washington system for NGC 419 and 416 I get about -0.1, which is the value you gave for NGC 121 also in the Small Cloud.

GASCOIGNE: Our abundances for NGC 121 and Lindsay 1 were based on the Washington system, too.

RICHER: I was interested in your statement about the presence of carbon stars setting the lower mass limit to intermediate ages for a cluster. After all, there are a few globular clusters in the galaxy that do have carbon stars and certainly there are field Population II carbon stars that are less than a solar mass. Theoreticians may now know how to make them, but nature certainly does.

GASCOIGNE: I'm no expert on carbon stars, but isn't the point here that those in the Clouds are very red, with B-V $\simeq$ 2.0 or redder, and lie beyond the tip of the giant branch.

HARWARDEN: Have those carbon stars been confirmed by spectroscopy then? A large number of the clusters associated with carbon stars in the Small Cloud were checked by Henry Albers on objective prism plates. He felt that most of the very red stars that had been regarded as carbon stars were in fact not carbon stars at all.

GASCOIGNE: Many have been confirmed spectroscopically as carbon stars, by Feast, Mould and Aaronson, and by Westerlund's group.

RICHER: If I could just comment on that. I've obtained slit spectra for the three very red stars in NGC 419, and they are all carbon stars, and the two very red stars in 2209 are also carbon stars. I believe Dr. Hardy also has some spectra.

FEAST: Lloyd Evans is following up some of the ones that he found that he suspected to be carbon stars from their colours, and I think he confirms that they are carbon stars. I think, if I could also say, there is a distinct difference between the carbon stars in old open clusters and the CH stars in globular clusters, so I think it *isn't* fair to make the kind of statement that Ben did.

RICHER: Well, it may be a question of semantics, but what is a carbon star? A carbon star has $C/O > 1$; beyond that one doesn't know how to . . .

COHEN: I think that the two carbon stars in Omega Centaurus for which I have echelle spectra, which are numbers 55 and 70, are bonified carbon stars. They have immense C_2 bands and nobody's going to call them a CH star by any stretch of the imagination. You have to consider them to be equivalent to the field carbon stars.

FEAST: But they don't sit in the same place in the HR diagram as the ones in the old open clusters.

COHEN: That may be, but . . .

FEAST: But that's the important point for the differentiation.

KRAFT: Didn't Mould and Aaronson find carbon stars in some of these clusters. I've forgotten the numbers.

GASCOIGNE: Yes. They picked them in the first instance by their very red colours, and according to their spectra about half were, in fact, carbon stars.

KRAFT: The major point is that the bolometric luminosities were so high that clearly this implied they had to be essentially young, isn't that correct?

RICHER: There's an error in their luminosities. They're about two magnitudes too bright.

(This discussion continues after Freeman's paper - Ed.)

https://doi.org/10.1017/S0074180900092044 Published online by Cambridge University Press