# GLOBULAR CLUSTER LUMINOSITY FUNCTIONS AND HELIUM ABUNDANCE DIFFERENCES ACROSS THE GALAXY

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This is a preliminary report on a project in which I have been comparing observed and theoretical giant branch luminosity functions for a relatively large number of globular clusters. I believe that I have found some novel evidence to support significant He differences among globulars, especially for the inner part of the galaxy, where He appears to be increasing toward the galactic center.

Bolometric luminosity functions (LF's) have been constructed for 17 clusters, using published photometry of the very largest and most complete samples of stars. To try to eliminate field stars, I considered only clusters with very clean CM diagrams, or those which have available proper motions, radial velocities, or two color data. Theoretical LF's appropriate to each cluster's observed [Fe/H] have been constructed from the red giant grids of Sweigart and Gross (1978), and from a 0.6 $M_{\odot}$ AGB track of Gingold's (1974). The theoretical LF's all assume the same red giant mass, 0.8 $M_{\odot}$, and the same Y, taken to be 0.30, and thus they differ from each other for the very small effect of the differing assumed metallicities. The advantage of LF's, as opposed to isochrones, is that one avoids all the problems associated with uncertainties in theoretical radii and colors.

I fit the LF's of the observed stars to the theoretical LF's in the most secure part of the magnitude range, i.e. above the horizontal branch and below the red giant tip. In effect, they were normalized in the range of $0.0 > M_{bol} > -3.0$. The original intention was to look at the numbers of stars on the HB, but I happened to notice that there were striking differences, from one cluster to another, between the observed and predicted numbers of stars at the red giant tip. This is intriguing because the theoretical models predict only minute luminosity variations at the tip, even with substantial changes in mass, chemical composition, etc.



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To quantify this variation, I calculated, for each cluster, the ratio of the observed number of stars with $M_{bol} < -3.0$, to the expected theoretical number in a sample of the same size. This ratio, dubbed $r$, is a measure of the height that the red giant branch (RGB) extends above the HB, independent of the sample size in a given cluster. That is, a low value of $r$ implies that the observed number of stars falls off at luminosities lower than the predicted luminosities, while a higher value of $r$ implies that there are more bright stars than expected. This assumes, of course, that the sample is large enough to have a reasonable statistical chance of containing stars this bright. This is indeed true for the clusters in my sample, because I specifically chose them to have large numbers of stars. In fact, $r$ does not correlate with the number of stars brighter than the HB in these cluster samples.

In addition, $r$ turns out to be uncorrelated with metallicity, integrated spectral type, $(B-V)_{o,g}$, $S$, distance from the Sun, concentration class of the cluster, the annulus the photometry was done in, or any other property of the cluster. What it does correlate with, at least for my original group of 11 clusters, all with $R_{GC}$<10 kpc, is galactocentric distance (Figure 1).

The error bars on this graph need some discussion because, unfortunately, they are not the standard errors. It turns out that any reasonable estimates of the errors in reddening, distance modulus, B.C., and [Fe/H], have essentially negligible effects on the positions of the points in this graph. In order for a cluster at 5 kpc to have the same relative number of stars as do clusters near 10 kpc, for example, any errors would have to add up to the equivalent of 0.75 mag increase in distance modulus. What the error bars on the graph do show is the effect of adding or subtracting a star from the observed sample of the red giant tip. The errors are large, because the number of stars in

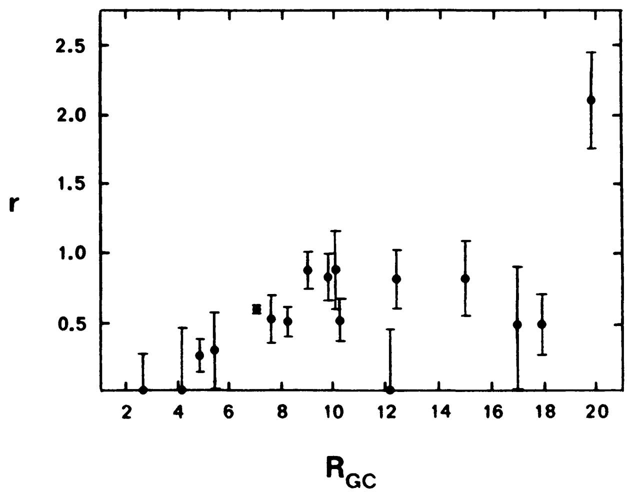


Figure 1. $r$ vs $R_{GC}$ for a sample of 17 globular clusters.

this part of the diagram is small, even with the largest and most carefully selected samples available. This dependence on small number statistics is a major defect of this representation. It also probably explains why this phenomenon has not been examined in detail before. Work is now in progress to find a more significant way to demonstrate these differences in LF's.

In the meantime, it is still hard to believe that this apparent correlation is entirely an artifact of small number statistics. For one thing, a cluster like M55 (near 5 kpc) should have many more bright stars, as it was the second largest sample (after ω Cen) of the 17. Also, the numbers of observed stars at the red giant tip are not likely to be in error by more than one star, because there exists definite proof of membership for almost every single one of these bright stars.

Note that this parameter *r* correlates more tightly with galactocentric distance, for $R_{GC}<10$ kpc, than does any other globular cluster parameter. If the correlation is real, it clearly indicates that clusters at different distances from the center do not all fit theoretical models with the same age, mass, and chemical composition. (Since [Fe/H] is already taken into account, that means Y or CNO/Fe.)

Now consider the clusters with distances greater than 10 kpc, and the diagram becomes much less straightforward. One reason is that the outer points are much less trustworthy individually. These clusters are fewer, fainter, and not as well studied, so that the average sample size was much smaller than for the inner clusters. Also, in two cases, for NGC5466 and M3, it was necessary to transform the old *P*,*V* photometry onto the *B*,*V* system, and that introduces more error. The overall trend is probably correct, however.

Having said that, now let me point out that four out of the five clusters between 12 and 18 kpc, which fall below a continuation of a straight line relation, are so-called second parameter clusters in their HB morphology. That is, they have redder HB's than other clusters of equivalent metallicity. M79, at 20 kpc and $r > 2.0$, has by contrast a typically very blue HB, with few RR Lyrae stars. This graph then corresponds directly to Searle and Zinn's (1978) findings, in that, inside about 10 kpc, everything is neat and well behaved and there are apparently no anomalously red HB's. Outside 10 kpc, there is a lot of scatter which appears to be related to the second parameter phenomenon.

It is not clear what this means in terms of $r$, so for now I will consider only the linear relation defined by clusters in the inner part of the galaxy. If the normal clusters do follow such a relation, we need to explain a progression in the clusters' CM diagrams like that shown in Figure 2. This very schematic drawing shows how the CM diagrams would actually appear for three typical clusters of the same metallicity, with the same number of stars, at the indicated positions in the galaxy. With real clusters, of course, and data containing very different numbers of stars, this isn't at all obvious until the data are normalized in some fashion.

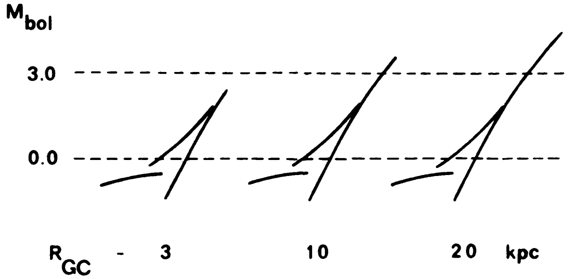


Figure 2. Schematic colour-magnitude diagrams (see text).

Since theory predicts only tiny luminosity variations at the first red giant tip, the most obvious explanation is that this reflects differences in the numbers, and hence in the masses of asymptotic giant branch (AGB) stars in different clusters.

Unfortunately, this does not work. First of all, the four clusters closest to the galactic center have too few stars at the red giant tip, compared to the numbers at lower luminosities, to completely account for the first RGB, even if there are no bright AGB stars. Second, if turnoff masses in clusters at large galactocentric distances are significantly larger than the turnoff masses of stars in inner clusters, then M92 and M13, among others, would need to be billions of years younger than clusters nearer the center. Besides being difficult for galaxy formation models, this would make it even harder to explain their HB morphology. If one tries to account for the AGB mass difference by mass loss processes, one must explain why both metal-rich and metal-poor clusters at the galactic center lose a lot of mass; and why clusters of all metallicites further away lose relatively little.

Similar difficulties are met if the correlation is attributed to CNO variations, different rotation rates, etc. The only plausible explanation appears to be that the helium abundance varies sufficiently from cluster to cluster, increasing toward the galactic center, to affect the CM diagrams. The reason that Y produces this effect on the apparent height of the HB has less to do with the luminosity change at the tip than with the effect of Y on the HB luminosity. An increased Y in clusters toward the center would necessarily make their HB's brighter, which affects their assumed distance modulus. I would like to suggest that HB luminosities vary systematically across the galaxy in a way which correlates much less with [Fe/H], than with $R_{GC}$ (and hence, Y).

This sort of a suggestion is not to be made lightly, especially since the main evidence comes from collections of small numbers, so I would like to point out some additional facts in favor of this view.

First, one consequence of higher Y is a bluer HB. NGC6171 ($\sim$3 kpc) and NGC6723 ($\sim$4 kpc) are both quite metal rich clusters, comparable to or slightly less than 47 Tuc, but they have significant numbers of RR Lyrae stars and even some stars to the blue of the instability strip. M55 and M10 (between 5 and 6 kpc) are less conclusive, since their metal abundances are much lower, but still they have quite blue HB's. Since the effect of Y on most metallicity indicators in the CM diagram is exactly opposite to that of Z, we might be systematically underestimating the metallicity of clusters very near the galactic center. (As an aside, I might point out that both 47 Tuc and M71, our standards of comparison for metal rich globulars, are both way out at 7 or 8 kpc.)

Second, consider the width and shape of the RGB's. An examination of the Dudley Observatory catalog (Philip, Cullen, and White, 1976) shows that many clusters very near the galactic center appear to have very wide stubby RGB's. This could conceivably be due to field stars or poor photometry. At least in the case of NGC6171, however, the width of the RGB seen in an early study by Sandage and Katem (1964) was confirmed by Dickens and Rolland (1972), who concluded it could be due to AGB stars. (If there are a substantial number of field stars, the ratio of HB to RGB stars might be very unusually large, however.) Contrast this with typical examples of outer clusters, with much taller and thinner RGB's, regardless of metallicity. In view of Figure 2, this appears to be part of a pattern which should be investigated.

Third, in the magnitude range where I fit the observed to the theoretical LF's, the best fits happened to be for clusters with $r$ near 0.6. If the distance moduli of other clusters were changed to make clusters with smaller $r$ brighter, and clusters with larger $r$ fainter, many of the fits would improve.

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There are two points I would like to stress. Figure 1 does not in itself say anything about age differences, except that whatever causes this correlation for $R_{GC}$ less than 10 kpc either completely dominates the effects of any age scatter on *r*, or is itself closely correlated with age. Furthermore, even if *r* does imply Y, this only complicates the second parameter problem, because at least one other parameter is still needed to explain the HB's; i.e., M13 and M3 still have the same Y apparently, because *r* is essentially the same.

Another point, or rather a warning, is that since all the observable CM diagram parameters depend on Y, such as position of the MS, luminosity of the HB, colors of the RGB and HB, etc., it is probably not valid to directly compare the CM diagrams of clusters at vastly different $R_{GC}$, in order to get distance moduli, reddenings, metallicities, etc. There will probably be systematic effects.

I hope to eventually be able to give a quantitative answer for the size of the He differences one can expect from these differences in the LF's. In the meantime, I would like to make the mandatory plea for more observations. I think it would be extremely interesting to do high dispersion spectroscopy for stars in clusters very near the galactic center to see what their metal abundances really are. Also I think that more, careful, and fainter CM diagrams, with *membership criteria*, are needed for these clusters, as well as ones at large galactocentric distances. It may be true that we won't really understand the clusters nearest us until we understand more about the more distant ones.

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DISCUSSION

*Schommer:* Three comments. That's really very interesting. There are two points that I think you should put on the diagram. One is Draco because I think Stetson's photometry is certainly reliable.

*GREEN:* But what is Draco?

*SCHOMMER:* I don't know what it is. And the other point is NGC 2419 that Harris and Racine did at a large galactocentric distance. It would be very interesting to see where those two lie.

*GREEN:* I agree with you. But my concern with Draco is that, when I started this, I had the feeling from lack of anything else that the masses and compositions for galactic globular clusters might be similar enough so that you can compare them to, essentially, the same theoretical luminosity function. If Draco has much different masses then I'm not sure that's valid. I can do it, but I'm not sure what it'll say. For 2419, I need a proper motion survey; there are so many field stars in the diagram: look at it - it's full of field stars. I tried it. I looked at it long and lovingly, because it is one of these long, skinny, typical, outer ones with a very blue horozintal branch and I would have loved to have done it, but I couldn't trust the data.

*SCHOMMER:* My second comment is that, having done some photometry myself, one doesn't always have to attribute it to cruddy photometry. I think the field star problem is more severe on the giant branches of these clusters.

*GREEN:* Well, for the stars I used in 6171, you can find this even if you just look at the rings very close to the centre. It doesn't matter. You can add in rings going out from the centre. To the point where the diagram is still quite clear, you get a large number of stars and you can still see the same effect.

*SCHOMMER:* And the third point is, since Davis Philip is here, it is the *Dudley Observatory Catalog*.

*GREEN:* Excuse me, what did I say?

*SCHOMMER:* You said DDO.

*GREEN:* Oh. I'm sorry - really sorry.

*PHILIP:* Is that what you were trying to say?

*GREEN:* That was a slip of the tongue.

*KRAFT:* What $\Delta Y/\Delta Z$ would you have to have in order to have this?

*GREEN:* That's what I apologized for at the end. I don't know. Part of this effect is due to the fact that if you change Y, you change the main sequence lifetimes, and thus the turnoff masses for clusters of higher Y have to be considerably lower unless you're willing to accept a something like a 10-15 $\times 10^9$y spread in

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ages. You need lower turnoff mass, and as soon as you have lower turnoff mass from the main sequence, then part of the blue effect from the horizontal branch comes from low masses and part from helium abundance. Part of the height of the red giant tip above the horizontal branch comes from the mass and part from helium. I suspect that the helium abundance has a stronger effect, because the helium abundance is the one that directly affects the luminosity of the horizontal branch and mass doesn't do that so much, but I can't quite separate it.

*KRAFT:* The problem is that you can't do the photometry down to the main sequence in most of those clusters because they are in crowded fields.

*GREEN:* It is not even clear to me that it would help, because the position of the main sequence is affected by the helium abundance. If you increase the luminosity of the horizontal branch, you also increase the luminosity of the main sequence. There may be differences, but we must remember the emphasis that was given to the fact that main sequence photometry is very difficult. Increasing the Z makes the main sequence go apparently to the right or down, depending on the way you look at it. Right? That is the same as decreasing Y. Increasing Y makes the main sequence go up or to the right.

*KRAFT:* No, it's the other way around. You get a bigger separation.

*KING:* But, in either case they go in inverse directions, don't they? They compensate each other.

*RENZINI:* That's right - they go opposite.

*GREEN:* They're opposites. O.K. Then it would be very valuable.

*CAYREL:* If Z and Y vary the same way, then you don't see anything.

*GREEN:* People think the metallicities of at least some clusters in the galactic centre are relatively metal poor. If that turns out to be the case, and not that we've underestimated it, then maybe you should see something, but in order to do that, you need spectroscopic analysis of the stars.

*FREEMAN:* Just one observational thing which I think might be possible. Some of the clusters, at least, have these UV-bright stars which are quite bright things, around -3, and they're O to B stars. I believe, though, I don't know from my own experience it is possible to measure reliable helium abundancies for these, unlike the horizontal branch.

*GREEN:* But does that do you any good by that stage of the evolution?

*FREEMAN:* It might well do, I don't know.

*GREEN:* Well, if you see larger helium abundances, you can attribute it to mixing during previous phases. If you see smaller helium abundances, you can say that it all diffused inwards. It seems to me to be an explanation for everything. (Laughter).

*STRAIZYS:* What range of helium abundance is necessary to explain this correlation? And, is it possible to check this relation by helium abundances determined by other methods such as the blue edge of the RR Lyrae strip?

*GREEN:* To your first question, I hope to have an answer, but I don't have it yet. And I'm not sure how good the limits are that I'll be able to set on it. To your second question, I looked at other methods of determining helium abundance, for example, the width of the stellar instability strip. It seems to me that the inaccuracies in other methods of determining it give you sufficient slop so that you can't. That's the reason why it hasn't been well determined before, because these other methods give you answers where the errors are as wide as the effect you are trying to measure. When the Los Alamos group published that paper on the width of the instability strip, I went down their clusters and looked at my clusters and it seemed to me that there certainly wasn't any inconsistency. NGC6171 was on their list and it has apparently a rather wide instability strip. Well, their results are not inconsistent with what I have.

*ROSSI:* If I remember correctly, Mallia detected spectoscopically that in some clusters where helium abundance was lower than normal in the blue horizontal part, it began to be normal in the red giant part.

*GREEN:* How is helium abundance determined?

*ROSSI:* Spectroscopically.

*GREEN:* Well, it seems to me that there are other explanations for that, in that by the time you get to the very blue stars you necessarily have a very small envelope mass, but a large core mass. Thus any kind of an effect that you can get in the atmosphere, diffusion or mixing, anything you can come up with is going to enhance it in those stars.

*ROSSI:* Yes, but if diffusion is the reason for helium under-abundance, it doesn't alter very much the evolutionary tracks.

*KING:* May I suggest that I put a finger on this poster paper and perhaps Dr. Rossi will be standing by his poster paper to continue this discussion at length with anyone who wants to know where helium goes. There will be a recess now.