Is there a metallicity gradient in the LMC?

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ABSTRACT
A small but significant radial gradient in the mean periods of LMC RR Lyrae variables is established from the OGLEIII survey data. This is interpreted as a metallicity gradient but other possibilities are discussed. Data on the ratio of photometrically selected C- and M-type AGB stars in the LMC, kindly provided by M-R. L. Cioni, are reanalysed. Removing the effects of bias leads to conclusions strikingly different to the original ones. There is a slight gradient of the C/M ratio in the inner part of the LMC which might be due to a very small mean metallicity gradient. In the outer part of the LMC the C/M ratio drops dramatically. The most likely reason for this is that the proportion of older stars increases in the outer regions. The mean metallicity of the inner AGB star population estimated from the C/M ratio is lower than for intermediate age LMC clusters and suggest that this population is in the mean older than the clusters and has a mean age which falls in the LMC cluster age gap.

Key words:

1 INTRODUCTION
To understand the origin and evolution of the LMC we need to know how objects of different ages and metallicities are distributed within it. A step in this direction is to establish whether there are metallicity gradients in LMC objects of various types. Pagel et al. (1978) discussed the oxygen abundance of LMC H\textsc{ii} regions and found marginal evidence for a decrease outwards from the centre. More recently a radial metallicity gradient for the AGB star population has been discussed by Cioni (2009)(=C09) who also summarized other relevant work. In the present paper we report a search for a possible metallicity gradient in the RR Lyrae population based on the LMC RR Lyraes discovered by the OGLE group (OGLE-III, Soszyński et al. 2009 = S09) together with a period-metallicity relation. The RR Lyrae, as tracers of the oldest populations, are particularly important for understanding the early history of the LMC. We also compare our results with previous work including a reanalysis of the metallicity gradient from AGB stars.

2 THE PERIOD-METALLICITY RELATION
A number of authors have discussed the relation between period and metallicity for Galactic RRab Lyrae stars (fundamental mode RR Lyraes). Fig. 1 is a plot of such data, kindly provided by Dr A. Layden. Also shown in the figure are data for the LMC. For these, the spectroscopic values of [Fe/H] derived by Gratton et al. (2004) and Borissova et al. (2006) were used. Two lines are shown in the figure. The dotted line is a least square fit to the Layden data. This has the relation:

\[ [\text{Fe/H}] = -5.62(\pm 0.47) \log P_{\text{ab}} - 2.81(\pm 0.13), \sigma = 0.42. \] \hfill (1)

The solid line is given by:

\[ [\text{Fe/H}] = -7.82 \log P_{\text{ab}} - 3.43, \sigma = 0.45, \] \hfill (2)

which is the relation used by Sarajedini et al. (2006) for an investigation similar to the present one, but on RR Lyraes in M33. It is based on a slightly different sample of Galactic RR
Lyrae which was also supplied to them by Dr A. Layden. Evidently the Galactic data show a clear trend though with considerable scatter. The LMC data generally lie together with the Galactic points. We shall assume that LMC RR Lyrae follow the Galactic relation and discuss below the effect of possible deviations from it.

Suggestions have been made that a relation involving both period and light curve shape gives an improved method for estimating metallicity (e.g. Jurcsik & Kovács 1996). We tested this for the available LMC light-curve parameters (S09) and found no improvement in that case. Our analysis is therefore based on equations 1 and 2.

3 THE LMC METALLICITY GRADIENT FOR RRAB VARIABLES

The LMC OGLE-III catalogue lists 17,693 RRab stars. Most of these are confined to a limited magnitude range (e.g. S09 fig. 7). There are, however, a small number at brighter magnitudes. These are likely to include blended stars and foreground objects. We have therefore omitted all stars with $I < 18.3$ mag. Tests show that including or omitting these data does not affect our results in any significant way. We have also omitted all RR Lyraes marked by S09 as blended or questionable and also those in the region of LMC globular clusters as defined by S09. This left us with a sample of 16,864 RRab stars.

In her discussion of the metallicity distribution of AGB stars, Cioni (C09) adopts a model for the LMC which is essentially that of a disc inclined to the plane of the sky. The true three dimensional distribution of RR Lyraes in the LMC is not at present known and, as a first approximation, we follow the model used by Cioni. This adopts an inclination of $34.7^\circ$, a position angle of the major axis of $189.3^\circ$ and an LMC distance of 51kpc. Changing the distance will not significantly change any conclusions and Cioni’s distance is adopted so that a direct comparison can be made with her results. Using this model we derive the distance $R_{GC}$ of a variable for the centre of the LMC, taken (with Cioni) to be $\alpha = 82.25$ and $\delta = -69.5^\circ$.

For each RRab star we derive an estimate of $[\text{Fe/}H]$ from equations 1 or 2 and use these data to obtain mean $[\text{Fe/}H]$ in concentric annuli about the centre. The results are shown plotted in Fig. 2. The errors are internal, i.e. they not include the uncertainties in equations 1 and 2. Fig. 2 indicates a mild systematic gradient outward and least square fits are shown. These are, based on equation 1:

$$[\text{Fe/}H] = -0.0104(\pm 0.0021) R_{GC} - 1.4213(\pm 0.0046), \quad (3)$$

and based on equation 2:

$$[\text{Fe/}H] = -0.0145(\pm 0.0029) R_{GC} - 1.4976(\pm 0.0063). \quad (4)$$

These two relations (equations 3 and 4) give nearly equal gradients. The absolute values of the metallicities differ by less than the standard error of the zero-point in equation 1.

The longer period RRab stars are on average more metal poor and also of lower light amplitude than the shorter period ones. One might therefore be concerned that the above results could be affected by a lower efficiency of finding low amplitude variables in the more crowded regions of the LMC. We have made an attempt to check whether this is a significant effect by determining the ratio of the number of RRab stars to RRc stars as a function of distance, $R_{GC}$, from the centre. The overtone, RRc, variables are of lower amplitude than corresponding RRab stars. Thus, other things being equal, a selection effect should show as an increase of the $N_{ab}/N_{c}$ ratio (loss of RRc variables) in the inner parts. Fig. 3 shows no evidence of this. If anything there may be a slight decrease in the ratio in the inner parts, but this is quite uncertain. Of course the ratio may well depend on metallicity, but at least in the Galactic globular cluster population this works in the sense that the ratio is smaller in the more metal-poor clusters.

As already noted, Gratton et al. (2004) and Borissova et al. (2006) have derived estimates of $[\text{Fe/}H]$ in the LMC from low resolution spectra. Fig. 4 shows their results plotted against $R_{GC}$. Variables in the region of LMC globular clusters are omitted. A least squares fit to the data is shown, this has the form:

$$[\text{Fe/}H] = -0.050(\pm 0.037) R_{GC} - 1.480(\pm 0.045), \sigma = 0.18. \quad (5)$$

These data, which cover the inner region of the LMC agree with the results from the period distribution within the uncertainties; though taken by themselves they do not provide convincing evidence of a metallicity gradient.

The results summarized in Fig. 2 depend on the assump-
tion that the LMC RR Lyraes follow the same mean period - [Fe/H] relation as the Galactic stars. This assumption cannot be tested directly. The LMC RR Lyraes with spectroscopic abundances plotted in Fig. 1 lie with the Galactic points. However, their small number, their limited range in [Fe/H] and the substantial intrinsic scatter in log $P_{ab}$ at a given metallicity $^{[1]}$ precludes any attempt to derive an independent slope to the relation. A referee has suggested that we should consider the case when there is no relation between [Fe/H] and period and that there might in fact be no metallicity gradient for this population. Since Fig. 2 is simply a scaled version of a mean log $P$ - $R_{GC}$ relation, the gradient in mean log $P$ must then be explained in terms other than [Fe/H]. A model with a nearly constant mean [Fe/H] for the RR Lyraes, but with an age gradient might be possible. It will be clear that our favoured model of a metallicity gradient might well also imply an age gradient. More complex models might be developed. However, they will all involve a systematic radial gradient in RR Lyrae properties.

4 A POSSIBLE METALLICITY GRADIENT FOR THE AGB STAR POPULATION

Battinelli & Demers (2005) suggested that in a stellar system the ratio of carbon-rich to oxygen-rich AGB stars was a function of [Fe/H] and a rederivation of this relationship was given by C09 who found:

$$[Fe/H] = -0.47(\pm0.10) \log(C/M) - 1.39(\pm0.06),$$

though with considerable scatter as can be seen from fig. B1 of C09.

Cioni & Habing (2003) selected likely LMC AGB stars (i.e. they were brighter than an adopted tip of the RGB) from the DENIS survey in $IJK$, and divided them into probable C and M stars using colour criteria. These data have been used by C09 to study the C/M number ratio and to estimate [Fe/H] using equation 6 as a function of distance from the centre of the LMC. In this work, the numbers of likely C and M stars were counted in bins of size 0.04 square degrees over a grid of 100 $\times$ 100 bins.

Dr Cioni has very kindly placed these counts at our disposal. We proceed as in subsection 3 and calculate the value of $R_{GC}$ for each bin and then sum all the likely C and M stars in the bins lying in annuli about the centre.

The results are plotted in Fig. 5. This figure shows a very slight increase in C/M from $R_{GC} = 1$ to $R_{GC} = 4$ kpc. If this is taken as significant it represents, using equation 6, a decrease in [Fe/H] from $\sim -1.07$ in the centre to $\sim -1.10$ at $R_{GC} \sim 4$ kpc. It seems to us that the drop in C/M at greater values of $R_{GC}$ can be hardly be attributed to an increase in mean metallicity. It seems much more likely that this is due to a change in age of the dominant population. It is natural to assume that this is due to older populations being more prominent on the outskirts of the LMC. These, of course, might be metal poor.

These conclusions are surprisingly different from those in C09 and we are very grateful to Dr Cioni for send us details of her work. This consisted of deriving the C/M for each bin and these, converted to [Fe/H] using equation 6 are plotted in C09 fig. 2. A problem arises in this case since in the outer parts of the LMC the number of C or M stars per bin is very small and may be zero. For instance in the annulus at $R_{GC} = 3.76kpc$, there are 408 bins of which 4 have no M stars, 96 have no C stars and two have neither C nor M stars. The procedure in C09 was to omit bins when either the number of likely C stars or M stars was zero. Since in general C/M $< 1$, this will tend to bias the results towards higher C/M ratios. That this is a significant effect can be seen from Fig. 6 which shows results from counts in annuli as before, but now with all bins omitted which have no likely C stars or M stars. Within the uncertainties and the question of assigning proper weight to individual bins, Fig. 6 converted to [Fe/H] by equation 6 would replicate the results of C09. Thus we believe these results are significantly affected by this selection procedure.

It is at first sight rather strange than in an initial discussion of these data Cioni & Habing (2003) obtained a plot (their fig. 3) which appears to show a ring of larger than average C/M values in the outer parts. This used data from individual bins. A possible explanation of this is as follows. The apparent ring occurs in regions where the number of stars per bin is small and thus the standard error of a C/M  

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$^{[1]}$ A substantial range of periods at a given metallicity is expected in view of the range of periods in a given globular cluster.
The ratio is large. Thus even if C/M were in the mean constant the scatter (which will be skew) increases as the number of stars per bin decreases and leads to the occurrence of some large ratios in the outer parts. It is possible that this, together with the very slight apparent maximum in mean C/M at $R_{GC} \sim 4$ kpc in our work (Fig. 5), is enough to produce the apparent effect seen in the Cioni & Habing figure.

During a study of the C09 data we found that, whilst the distribution of C stars among the bins of a given annulus was apparently random in the outer regions, it was not random in the more populated inner regions. This suggests real variations of density at a given $R_{GC}$ and deserves further study.

5 COMPARISON WITH OTHER TYPES OF OBJECTS

Pagel et al. (1978) obtained oxygen abundances for HII regions spread over the LMC. They found:

$$12 + \log(O/H) = -0.03(\pm0.02)\rho + 8.46(\pm0.06),$$

(7)

over a range of galactocentric distance $\rho$ of 0 to 4 kpc. Note that the parameters they used to derive $\rho$ are slightly different from those used to obtain $R_{GC}$. This will not make any qualitative difference to the result. As Pagel et al. remark, a spatial gradient is evidently small or absent in this young population.

Grocholski et al. (2006, 2007) have discussed metallicities of clusters in the LMC. Very old clusters (SWB class VII) have low metallicities ([Fe/H] $\sim -1.7$) and are widely distributed over the LMC. Clusters of intermediate age have a nearly constant metallicity: a mean [Fe/H] of −0.66 using metallicities corrected according to the prescription of C09. There is no evidence of a gradient from $R_{GC} = 1$ to 6 kpc (see C09 fig. 2). The intermediate age cluster NGC 1718 in outer part of the LMC is an exception to this with [Fe/H] $\sim -0.8$. However, there is some uncertainty regarding this cluster (Grocholski et al. 2006 appendix A.1). If we adopt the C/M calibration used by C09 (eq.6) together with our analysis (Fig. 5) the population out to $R_{GC} \sim 4$ kpc discussed in section 4 above, has a distinctly lower mean metallicity ([Fe/H] $\sim -1.1$) than the intermediate age clusters. In that case it presumably refers to the mean in a somewhat older population. This age then falls in the well known LMC cluster age gap where there are no known clusters with ages between $\sim 3$ and 10+ Gyr (see for instance the summary by Da Costa 1991).

The mean metallicities of field RGB stars (e.g. Carrera et al. (2008) are more or less constant out to $R_{GC} \sim 6$ kpc and are similar (on the scale of C09) to those of the intermediate age clusters but with a lower abundance ([Fe/H] $\sim -0.8$ on the C09 scale) at $\sim 8$kpc. There is also evidence of a smaller component with [Fe/H] $\sim -1.2$ (see C09 and references there).

6 CONCLUSIONS

Applying a period - [Fe/H] relation to the LMC RR Lyrae OGLE-III data base we find that these stars show, in the mean, a small but significant radial gradient in metallicity for distances out to beyond 5 kpc from the LMC centre. RR Lyraes with spectroscopically estimated metallicities agree with this result, though taken on their own the trend they show is only of marginal significance. These results would evidently be consistent with the classical picture of galactic evolution by the gradual collapse of a gas cloud.

A reanalysis of the data of C09 indicates that the C/M ratio of AGB stars shows a very small change out to $\sim 4$kpc from the LMC centre and then decreases dramatically. We attribute this decrease to an increasing importance of an older population in the outer parts of the LMC. The very slight increase in C/M from $R_{GC} = 1$ to 4 kpc, if real, could be due to factors such as age as well as metallicity and may also be affected by uncertainties in assigning stars to the C or M classes on the basis of photometric criteria. The AGB population studied is apparently less metal rich than the intermediate age clusters in the LMC, suggesting that in the mean this AGB population is older than the clusters and has an age in the LMC cluster age gap.

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