Referee's comments and suggestions (Revision 2)

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Abstract

We thank the referee for this second detailed revision of our article.

Below are the responses to the referee's comments and suggestions, following their numbering.

9 Sect. 3.4, paragraph 2

With respect to the weight given in the fit process, the likelihood used in this work treats all bins in the same manner. This is, no "strong weight" is given to the post-MS region, or any other region of the CMD.

For low mass clusters the stochastic effects will indeed be much more noticeable. This reflects in the fact that those clusters with the lowest mass estimates, are generally those which present more issues in their matching. These issues are mentioned throughout the article a number of times:

* **Sect. 5**: "We find in Appendix A that the code will slightly underestimate the masses by approximately 200 $M_{\odot}$, for low mass clusters."
* **Sect. 5.2.1**: "The standard deviation of the average relative mass differences decreases for larger masses (see Fig. 9) as expected, pointing to a more accurate recovery of the true total mass by `ASteCA`, as the clusters grow in size."
* **Appendix A**: "For low mass clusters – 500 $M_{\odot}$ or 1000 $M_{\odot}$ – the code assigns masses in a range between $\sim$200$-$3000 $M_{\odot}$. In this region `ASteCA` underestimates clusters' masses by $\sim$200 $M_{\odot}$. This effect is tied to an improper age estimation, where `ASteCA` incorrectly assigns younger ages to scarcely populated clusters, and compensates the low number of stars by decreasing the total mass. Such an issue is not unexpected for very low mass clusters."
* **Appendix A.1**: "Most of the poorest solutions obtained by `ASteCA` – those with $|\Delta z|$>0.01 dex – are associated to low mass scarcely populated clusters, with $\sim$40 true member stars on average (from two up to a hundred) in their analyzed CMDs. This poor solutions set is composed of 91 clusters – $\sim$12% of the sample – 58 of which have $M \leq 1000\,M_{\odot}$. Of these 58 low mass clusters, 38 are assigned younger ages by the code due to an improper field star decontamination process (an expected issue when the number of true members is very low)."

`ASteCA` does not currently provide a "goodness of fit" parameter. The best fit obtained by the code is relative to all the remaining synthetic CMDs analyzed (hundreds of thousands, or millions), but there's no value to quantify how good this fit is. The original article where the employed likelihood is derived (Dolphin 2002), gives a method to asses this goodness of fit (Sect. 2.6), but it isn't yet incorporated into the code. A coarse "goodness of fit" estimator are the uncertainties obtained for the best fit model. For low mass clusters, the stochasticity involved in their generation will impact as larger overall uncertainties assigned to its parameters. This is particularly noticeable for the age, as seen in Fig.1.

To address this point more directly we added a sentence to the end of paragraph two in this section, and another in the second to last paragraph of Sect. 4.

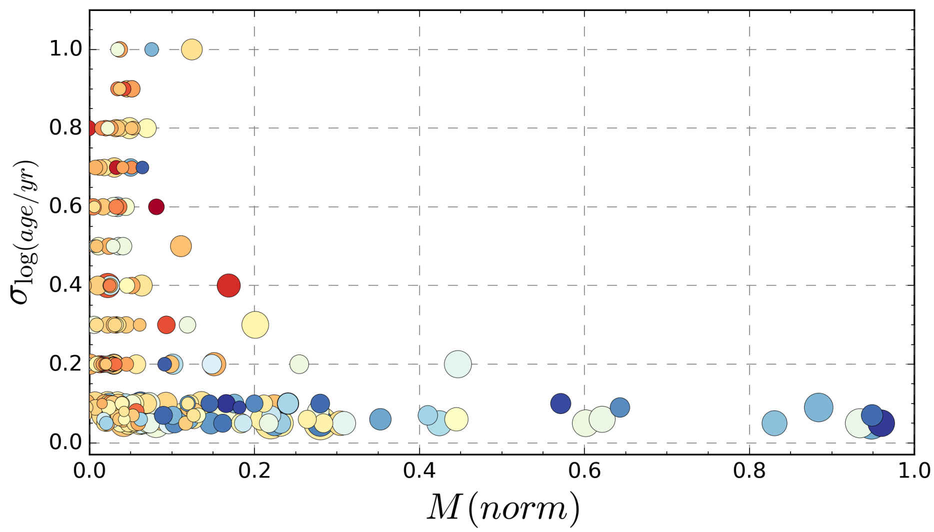

Figure 1: Distribution of log(age) errors versus (normalized) masses.

13 Sect. 4, paragraph 5

We could use $z/z_\odot$ internally in `ASteCA`, but there would be nothing to gain from it (programmatically speaking). Since this is a simple re-scaling, it can be easily performed after the matching process is done. It wouldn't change the fact that converting to [Fe/H] involves a logarithm, and thus a mathematical dependence in the uncertainties of the form:

$$\begin{aligned} [F/H] &= \log(X)\ ;\ X = z/z_\odot \\ \sigma_{[Fe/H]} &= \sigma_X/[X \times \ln(10)]\ \ ;\ \ \sigma_X = \sigma_z \times z_\odot \end{aligned} \tag{1}$$

Hence if we used $z/z_\odot$ for the distribution of uncertainties in Fig 3, the result would look like Fig. 1 in the cover letter from Rev 1, only re-scaled. It wouldn't resolve the error dependence that arises in [Fe/H] due to the logarithm. Errors are thus purposely displayed using [Fe/H] (rather than z) to make the reader aware that [Fe/H] errors increase for low metallicities, for a mathematical reason.

18 Sect. 5.1, paragraph 9 (near bottom of page 9)

(Notice that this question is related to Sect. 5.1, not 5.2 as stated in the referee's letter)

The referee said that the "tidal radius of the cluster is typically significantly larger than the radius at which the surface number density of the cluster equals that of the field". The tidal radius is mathematically equivalent to the radius

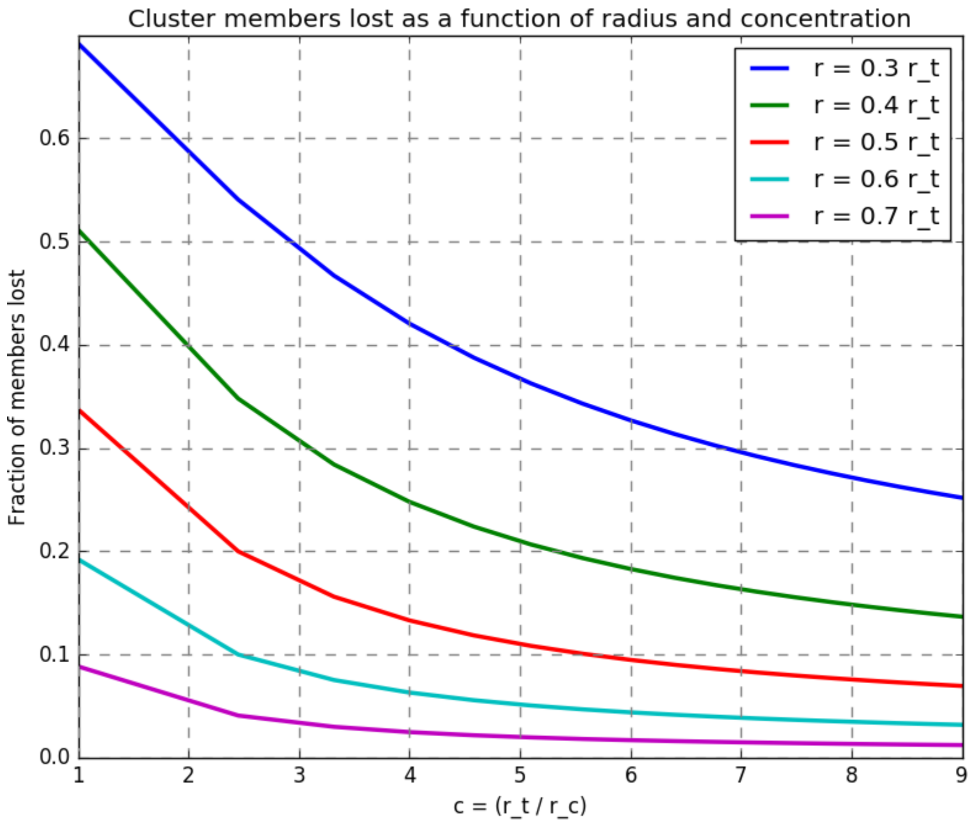

Figure 2: Fraction of cluster members that are lost using the density radius rather than the tidal radius, as a function of cluster concentration (assuming a King density profile). We show several density radii values, defined to be smaller (i.e., underestimated) than the tidal radius by given fractions.

where the number density of stars reaches the field density ("density radius"). This can be seen by solving King's number density function (King 1962, Eq. 14) for zero density (assuming the relation has been corrected for the field density), where the solution is $r = r_t$.

We assume that what the referee meant is that, *in practice*, the density radius is often set to more conservative values than the tidal radius.

Using Eq. 18 from King (1962), we can obtain the number of cluster members up to a given radius. We use a constant core radius and vary the tidal radius to process different concentrations ($c = r_t/r_c$). In Fig. 2 we show the fraction of total members lost, for five different density radius defined as fractions of the tidal radius. We can see that even if the density radius is underestimated by 50% ($r = 0.5r_t$), the number of stars that are lost reaches $\sim 30\%$ only for very low concentrations ($c < 1.5$), and drops rapidly for more concentrated clusters. In a cluster like NGC 419 for example, with $c = 6.9$ (Goudfrooij et al. 2014) underestimating the tidal radius by $\sim 50\%$ would result in losing less than 10% of its members.

Furthermore, according to the mass segregation effect, we know that low-mass stars are preferentially displaced towards the outer parts of the cluster (and eventually lost via evaporation). Hence, stars located between the density radius and the tidal radius, are mainly low-mass stars. These stars are mostly not detected due to the effects of limiting magnitude and photometric incompleteness (both accounted for in the synthetic CMD generation algorithm). Extending the density radius would thus include an even smaller percentage of cluster stars than those predicted above. For smaller low-concentration clusters, where the loss of members is seen to have a larger impact, the mass uncertainties are large enough to contain this effect.

We have added a paragraph in Sect 5.1 explaining the mass estimation in more depth, mentioning this effect. A footnote was also added to the second to last paragraph of this same section, also related to this effect.

19 Sect. 5.2.1

1. On the M/L relation of the H03 and P12 articles

We agree with the referee that the mass-age correlation is the reason for the discrepancies between these two parameters in the H03 and P12 articles. This is mentioned in the second to last paragraph of Sect 5.2.1: "These mass differences [between H03 and P12] are closely related to $\log(age/yr)$ differences."

To make this point clearer, we have made the following changes to the section:

1. Fig. 11 was expanded to show the age-mass correlation in different mass regimes. It was moved to the beginning of this section, and is now Fig. 9
2. The second to last paragraph from this section was moved to the beginning, and edited to reflect changes made to Fig. 11(9).
3. The old Fig. 10 was removed, as it became redundant after the changes made to Fig. 11(9).

Other changes made to Sect 5.2.1 are mentioned in the following point.

2. Issues related to crowding in the central regions of massive clusters

The referee is *absolutely correct* regarding the issue of crowding in our photometry. Even though we investigated the effects of complicated cluster features (such as the double red clump, or the extended main sequence turn-off), we failed to realize that the much simpler effect of crowding could account for the mass discrepancies found. Although `ASteCA` considers how other photometric effects alter the generated synthetic CMDs (limiting magnitude, faint stars incompleteness, photometric errors), it does not include the loss of stars in the central regions of a massive cluster due to photometric crowding. Since the mass estimation is based on the number of observed stars, losing a large portion of those will very clearly bias our results. The `ASteCA` code was originally developed to analyze open clusters, which is why crowding was never really an issue (until now of course). The effect of crowding on synthetic CMDs will be added to the code as soon as possible.

Our Washington photometry for the clusters NGC419, NGC1917, and NGC1751, show total numbers of estimated cluster stars around 2300, 170, and 200 in their cluster region CMDs. The synthetic CMDs of large masses (those given in the literature) show for these same clusters a number of members around 32700 (M=2.7×10^5 $M_\odot$), 3900 (M=8×10^4 $M_\odot$), and 6800 (M=7.2×10^4 $M_\odot$), for NGC419, NGC1917, and NGC1751 respectively. This means that, to account for the differences in the number of observed versus synthetic cluster stars, photometric crowding in our Washington data would need to be responsible for the loss of ∼95% of the stars present in the observed cluster regions. This percentage of lost stars in the cluster region couldn't be accounted for by any of the photometric process included in `ASteCA`.

We requested Dr Goudfrooij for the NGC419 and NGC1751 data used in Goudfrooij et al. (2014), who very kindly provided it to us. The photometric tables were generated from observations performed with the HST ACS/WFC instrument, which has a much higher resolution than our Washington photometry (0.05 arcsex/pixel versus 0.274 arcsec/pixel). The cluster data was processed with `ASteCA`, imposing a cut on $F555W$=23 mag to minimize the number of stars lost due to incompleteness (as instructed by Dr Goudfrooij). The fundamental parameters were fixed to those given in Goudfrooij et al. (2014), except the mass which was left to vary between $10^3 - 3{\times}10^5\,M_\odot$, and $10^3 - 10^5\,M_\odot$, for NGC419 and NGC1751 respectively. Fig.3 shows the result of this process. The mass estimated for NGC419 using the ACS/WFC dataset is $M{\approx}2.5{\times}10^5\,M_\odot$, very much in line with the average literature estimates of $M{\approx}2.7{\times}10^5\,M_\odot$. A similar result is found for NGC1751, for which a mass of $M{\approx}5{\times}10^4\,M_\odot$ is estimated, very close to the average Goudfrooij et al. value of $M{\approx}6.25{\times}10^4\,M_\odot$.

Imposing a similar cut on our NGC419 Washington data on T_1=22 mag (again, to minimize the loss of faint stars due to crowding) we find a mass estimate close to $10^5\,M_\odot$. This value is three times larger than our original estimate for this cluster ($2.8{\times}10^4\,M_\odot$), and around three times smaller than the estimate by Goudfrooij. While the mass difference is still somewhat large, this proves that reducing the loss of stars due to crowding improves our mass estimate substantially. Our mass validation study in Appendix A missed this effect, because the synthetic MASSCLEAN clusters are not affected by crowding.

We must conclude that the referee was right to question our conclusions regarding the mass estimates for larger clusters. The effect of photometric crowding in our Washington photometry is clearly the responsible for the systematic underestimation of masses, when compared to the integrated photometry studies.

To address the issues mentioned in this point, we have changed the section in the following way:

1. Sect 5.2.1 was substantially shortened and simplified. The exploration of other possible effects (double red clump, eMSTO, etc.) were removed, as they are no longer needed.
2. Table 4 (which showed the 5 clusters with the largest mass discrepancies) was removed.
3. The last paragraph was removed as it no longer reflects the overall conclusions of this section.
4. The stellar crowding in our photometry is mentioned as the effect responsible for the systematic mass differences.

Furthermore, the following changes were made to the rest of the article:

1. A sentence was added to the second to last paragraph of Sect 3.1 mentioning this effect.
2. The Conclusions were edited to reflect the above changes.
3. A sentence was added to the first paragraph of Appendix A, explaining that MASSCLEAN clusters are not affected by crowding.
4. Appendix D was removed, as it became irrelevant now that the reason for the mass discrepancies is clear.

22 Sect. 6.2, paragraph 5

Changed, as suggested by the referee. The sentences "Both MCs accumulate most clusters... The SMC has a larger proportion of..." that followed, were removed to accommodate the changes made in Sect 5.2.1.

References

Dolphin, A. E. 2002, Monthly Notices of the Royal Astronomical Society, 332, 91

Goudfrooij, P., Girardi, L., Kozhurina-Platais, V., et al. 2014, The Astrophysical Journal, 797, 35

King, I. 1962, ApJ, 67, 471

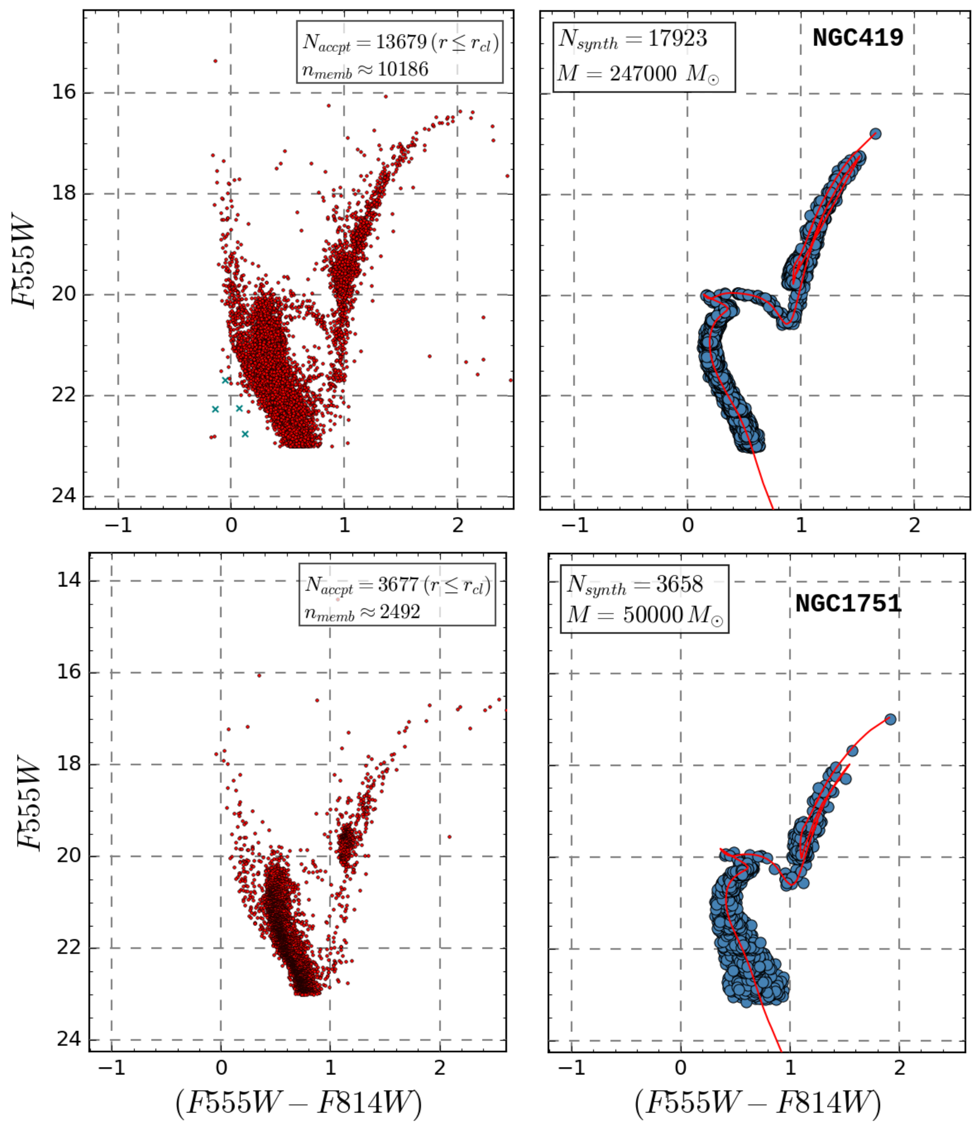

Figure 3: *Top left*: ACS/WFC CMD for NGC419 (data tables by Dr Goudfrooij), with limiting magnitude cut at $F555W = 23$ mag. *Top right*: best fit found by `ASteCA` for the mass (the rest of the parameters were fixed). *Bottom*: idem, for NGC1751.