On ageing star clusters using red supergiants independent of the fraction of interacting binary stars

J. J. Eldridge 1,*, Emma R. Beasor2,3† and N. Britavskiy4,5

1 Department of Physics, University of Auckland, Private Bag 92019, Auckland, New Zealand
2 NSF National Optical-Infrared Astronomy Research Laboratory, 950 N. Cherry Ave., Tucson, AZ 85719, USA
3 Astrophysics Research Institute, Liverpool John Moores University, 146 Brownlow Hill, Liverpool L3 5RF, UK
4 Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain
5 Departamento de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain

ABSTRACT
We use the Binary Population and Spectral Synthesis models to test the recent suggestion that red supergiants can provide an accurate age estimate of a coeval stellar population that is unaffected by interacting binary stars. Ages are estimated by using both the minimum luminosity of red supergiants and the mean luminosity of red supergiants in a cluster. We test these methods on a number of observed star clusters and find our results in agreement with previous estimates. Importantly, we find the difference between the ages derived from stellar population models with and without a realistic population of interacting binary stars is only a few hundred thousand years at most. We find that the mean luminosity of red supergiants in a cluster is the best method to determine the age of a cluster because it is based on the entire red supergiant population rather than using only the least luminous red supergiant.

Key words: binaries: general – stars: massive – supergiants – galaxies: star clusters: general.

1 INTRODUCTION
Determining the age of a resolved stellar cluster is a difficult process that has many uncertainties. One important and still unclear issue is the effects of rotation (e.g. Georgy et al. 2019) and interacting binaries (e.g. van Bever & Vanbeveren 1998). Especially, in changing the distribution of stars around the main-sequence turn-off, the primary feature used in age estimation. Both rotation and binaries allow stars to linger on the main sequence and be more luminous than would be expected from a simple non-rotating stellar model. The effect is obvious in old clusters as blue stragglers are clearly separated from the main-sequence turn-off while, in younger clusters the situation is less clear.

The contribution of both rotation and binary interactions to the main-sequence turn-off will be complex, and may also be age dependent. For example, recent studies have shown that there is a link between the position of a star in the main-sequence turn-off and its rotation velocity (e.g. Li et al. 2019; Sun et al. 2019a,b). However, trying to separate the importance of stellar rotation relative to binary interactions is difficult given that the most rapidly rotating stars most likely arise from binary interactions as described by de Mink et al. (2013). Therefore, while there is clearly a link between rotation and the distribution of stars in the main-sequence turn-off, it is not clear whether the distribution of rotation velocities is linked to the initial rotation velocity distribution or related to the population of interacting binaries within the stellar population. It would be useful if there was another method to determine the age of a star cluster that was not strongly affected by either binary interactions or stellar rotation.

Recently, both Beasor et al. (2019) and Britavskiy et al. (2019) have suggested a novel and accurate way to estimate the ages of star clusters by using the least luminous, and effectively the oldest, red supergiant (RSG). For these stars, the age of the star is greater than the time it spends in the evolutionary phase, which provides a tight age constraint. They also suggested that binary interactions such as mass transfer and mergers would only give rise to more luminous red straggler RSGs, relatively younger stars, that can be ignored.

Due to the significant implications of such a method providing a new insight into star cluster ages, as well as allowing future investigations into impact of interacting binaries on the turn-off star population, this idea should be tested further. In this letter, we investigate this idea using state-of-the-art theoretical stellar population models, from the Binary Population and Spectral Synthesis (BPASS) project, v2.2.1 (Eldridge et al. 2017; Stanway & Eldridge 2018). This code allows us to fully investigate the effect binary stars have on using RSGs for age determination.

* E-mail: j.eldridge@auckland.ac.nz
† Hubble Fellow
2 STELLAR POPULATION MODELS

We use the BPASS v2.2.1 models (see Eldridge et al. 2017; Stanway & Eldridge 2018, for full details) to synthesize RSG populations. We determine the minimum, maximum, and mean luminosities, and the standard deviation about the mean luminosity of RSGs versus age. Importantly, we do this for a population made solely of single stars and another that incorporates a realistic interacting binary star population based on the results of Moe & Di Stefano (2001).

We use results from three metallicities, with the metal mass fractions $Z = 0.004, 0.008, \text{ and } 0.020$. These are suitable for the Small Magellanic Cloud (SMC), Large Magellanic Cloud (LMC), and our Galaxy, respectively. We use the fiducial BPASS initial mass function with a minimum mass of $0.1M_\odot$, a slope of $dN/dM \propto -1.30$ up to $0.5M_\odot$, and a slope of $dN/dM \propto -2.35$ up to the maximum mass of $300M_\odot$.

To determine the nature of the RSG population at each BPASS logarithmic time bin of width 0.1 dex, we record the luminosities of RSGs, defined as stars that have completed core hydrogen burning and have a surface temperature of $\log(T_{\text{eff}}/K) \leq 3.66$. We search for the minimum luminosity and the maximum luminosity, and calculate the mean luminosity and the standard deviation.

We note that in star clusters it is unlikely that we observe RSGs at the minimum possible luminosity we predict in BPASS. Beasor et al. (2019) pointed out that RSGs evolve rapidly through those evolutionary phases. Beasor et al. (2019) therefore calculated a most likely minimum luminosity RSG by using the RSG luminosity distribution and sampling the lowest luminosity RSG, assuming 50 RSGs in a cluster. We have tested this method but found the result calculated is consistent with the luminosity given at the mean RSG luminosity minus the standard deviation of the population. This is reasonable as only 16% of RSGs would be below this limit. Furthermore, the most probable minimum luminosity of any RSGs will be close to this lower standard deviation. In this work, for simplicity, we take the most likely minimum RSG luminosity to be the luminosity defined by the distribution mean minus the distribution’s standard deviation at each time.

We show our derived distribution luminosity parameters for our RSG populations in Fig. 1. We can see that the minimum luminosities are close for single star and binary populations at early times but diverge at older ages. The binary population maximum luminosity is always significantly above that of single stars due to red stragglers. In comparison, the mean luminosities calculated are very close between single and binary populations. These luminosities also appear to provide a good age estimate up to approximately 100 Myr. However, beyond approximately 40 Myr, the distribution of expected luminosities increases due to increasing number of asymptotic giant branch (AGB) stars in the stellar populations.

As noted earlier, in Fig. 1 the minimum and maximum luminosities versus age are either lower or higher, respectively, for the binary population relative to the single star population. The higher maximum is due to mergers and mass transfer making more luminous RSGs at older ages than expected from a single star population as suggested by Britavskiy et al. (2019) and Beasor et al. (2019). The lower minimum luminosities are at odds with the expected assumption that the minimum luminosity RSGs are single stars. In fact, RSGs in a binary that fill their Roche lobe and lose mass all decrease in luminosity, which is a consistent prediction from binary evolution models (e.g. Wellstein, Langer & Braun 2001). Thus, including such interacting stars causes the minimum possible RSG luminosity to be lower and therefore whether an RSG is interacting with a companion should be checked. This will be observationally challenging. However, these lower luminosity binary stars are rare and the method employed by Beasor et al. (2019) using the most likely minimum luminosity still works. However, the standard deviation for the binary population is greater than that of the single star population.

In Fig. 1, we have overplotted the mean minimum luminosity calculated by Beasor et al. (2019). We can see that these lie on the lower $1\sigma$ line for our population up to 16 Myr after which the luminosity matches our mean luminosity line. The difference between the Beasor et al. (2019) and the BPASS lines provides an estimate of the systematic uncertainty that occurs due to our choice of stellar models. Beasor et al. (2019) used the MIST stellar models (Dotter 2016) and we have compared our single star models of the same initial mass to those to determine the reason for the difference. The initial mass range where the change occurs in the Beasor et al. (2019) relation is between 13 and $14M_\odot$.

A detailed comparison between the BPASS and MIST models is beyond the scope of this work. However, we have examined the models to understand where there might be a difference of the order of 0.1 dex in the expected minimum luminosities. Above $13M_\odot$, the stellar tracks are quite similar, although the BPASS models reach lower luminosities by 0.1 dex at the cool side of the Hertzsprung gap than the MIST models. However, the BPASS models also reach higher luminosities by 0.1 dex at the end of their evolution than the MIST tracks, so on average the mean luminosities are the same. The RSG lifetimes also appear similar, which suggests that the models, even with minor differences, agree to first order.

At $13M_\odot$ and below, blue loops (the movement on the Hertzsprung–Russell diagram during helium burning for lower mass stars) occur in some of the stellar tracks but again during the entire Hertzsprung gap model from MIST are 0.1 dex less luminous than the BPASS tracks. Then, during the RSG evolution, the lifetime of the MIST models is less than that of the BPASS models by a few hundred thousand years. The MIST models also tend to reach the RSG before the BPASS models, which together equates to older ages for an RSG of the same luminosity. The differences lead to the bump in the minimum luminosity line at 16 Myr.

We expect the stellar model has this behaviour due to the MIST tracks changing certain details around the MESA stellar models at this mass range. In comparison, BPASS models make no change to the numerical or physical details with stellar mass and this is represented by significantly smoother age–luminosity relations. As we have stated earlier, this does give an idea of the systematic uncertainty implicit in using an assumed stellar evolution model. We note that the BPASS tracks both single and binary have already been extensively validated against many observations of stars, e.g. Eldridge et al. (2017, 2019).

In light of all the above outlining the sensitivity of the most likely minimum luminosity RSG to many factors, we suggest another method to estimate a stellar population age with RSGs. This is to use the mean RSG luminosity calculated from all the RSGs in a cluster. This removes some (but not all) of the uncertainties between stellar models and importantly uses all the RSGs in a cluster rather than relying on the details of a single star. To evaluate how useful this method and that of using minimum luminosity RSG are, and how dependent on binary fraction the results are, we analyse the clusters discussed in Beasor et al. (2019) and Britavskiy et al. (2019) and other similar clusters for which data on the RSG population exist.
3 AGES OF OBSERVED CLUSTERS

We show the ages derived from RSGs for Galactic, LMC, and SMC clusters with RSGs in Fig. 2 and Table 1. We note that one of these clusters, Upper Sco, contains only one RSG, Antares. We see the age estimates using both the most likely minimum luminosity and mean luminosity lie within the range of previous estimates. The ages from the most likely minimum luminosity RSG tend to be higher than those estimated from the mean RSG luminosity.

The differences between the age estimates from our single star and binary star populations using the mean RSG luminosity are typically a few hundred thousand years, much smaller than the ages derived and within the uncertainty. This again reinforces the consistency of the idea that RSGs can be used to give useful age constraints on the age of stellar populations. The different ages from the single star and binary star populations for the most likely minimum luminosity estimate are typically a few times greater than that from the mean RSG luminosity. This confirms the hypothesis that a binary population-independent age estimate is possible by using the mean RSG luminosity in a cluster. Using the most likely minimum luminosity RSG may produce a small overestimate of the age. However, the values still agree within the calculated uncertainties.

We note that for the most likely minimum luminosity ages we have derived, we have not given the uncertainty in this value. They should be at least the same magnitude as those from the mean luminosity, but we expect these to be higher. One reason is that the slopes of the trends of luminosity in age in Fig. 1 are similar and thus a similar error in the luminosity will give the same error in the age. Another reason is that depending on just one star to estimate the age, we must consider whether we are truly sampling the RSG luminosity distribution well enough to have a star at the most likely minimum luminosity. To estimate the uncertainty, we would need to look at the RSG luminosity distribution at each age, sampling this with the number of observed RSGs to see what the distribution of luminosities we derive for the lowest luminosity RSG would be, as in Beasor et al. (2019). However, this requires a separate model for each individual cluster introducing extra computational cost.

Most of the clusters in our sample have ages in the range of 10–20 Myr. We note for clusters beyond this the discrepancy between the most likely minimum luminosity age and mean luminosity age is greatest, with the former overestimating the age significantly for several of the clusters. This again demonstrates the problematic nature of relying on a single star to derive an age.

The errors we present here are significant when considering the age on a linear scale as they are of the order of 0.15 dex or 40 per cent. The uncertainty in the luminosity of the RSGs is generally small, less than 0.1 dex. The same is true for the error in the mean luminosity (taken to be $\sigma/\sqrt{N}$). However, we see that the standard deviation of the mean luminosities derived from the BPASS models is also similar around 0.1 dex. Combining these uncertainties implies that there is always a minimum accuracy for any age estimate.

4 DISCUSSION AND CONCLUSIONS

We have used the BPASS stellar population models to investigate how interacting binary stars affect the accuracy of estimating star cluster ages using either the most likely minimum luminosity RSG or the mean RSG luminosity. While stellar mergers and mass gainers in stellar binaries will become more massive and more luminous RSGs than expected for a stellar population’s age, it was suggested by Britavskiy et al. (2019) and Beasor et al. (2019) that the minimum
luminosity RSGs are most likely to be the result of the evolution of an effectively single star. We found that less luminous RSGs can be formed by interacting binaries than expected from single star evolution. However, such stars will be rare and thus the most probable minimum luminosity RSG method of Beasor et al. (2019) is still applicable.

In Fig. 3, we compare all our different relations at different metallicities as well as those calculated by Beasor et al. (2019).

The relations vary due to metallicity and use of different stellar models. This suggests we must be wary that there is a systematic uncertainty in any age estimate using the RSGs that is dependent on the assumptions in the stellar models, whether that be the mass-loss rates, mixing scheme applied, or the initial metallicity.

However, while there is an offset, all the age–luminosity relations in Fig. 3 have a similar gradient. We note the relations from BPASS tend to be smoother than those calculated by the

Table 1. The ages of a number of Galactic (first five), LMC (second five), and SMC (last one) clusters estimated by using the minimum and mean luminosity of RSGs. The data are taken from Beasor et al. (2019, 2020) and Britavskiy et al. (2019). For the previous age estimate, we list the range and the best value from previous works that include Keller (1999), Keller, Bessell & Da Costa (2000), Clark et al. (2010), Negueruela et al. (2010), Marco & Negueruela (2013), and Origlia et al. (2019). Clusters indicated with an asterisk are ages calculated on the RSGs in the clusters that have been spectroscopically confirmed.

| Cluster          | Number of RSGs | $\log(L_{\text{min}}/L_\odot)$ | $\log(L_{\text{mean}}/L_\odot)$ | Previous estimate (Myr) | $L_{\text{min}}$ estimate (Myr) | $L_{\text{mean}}$ estimate (Myr) |
|------------------|----------------|-----------------|-----------------|------------------------|-------------------------------|-------------------------------|
| Upper Sco        | 1              | 4.99            | 4.99 ± 0.15     | 11                     | 10.1 ± 10.0                  | 10.8 ± 10.8                  |
| NGC 7419         | 5              | 4.37            | 4.58 ± 0.13     | 7.1–21                  | 18.9 ± 18.2                  | 15.9 ± 16.2                  |
| χ-Per            | 8              | 4.38            | 4.68 ± 0.07     | 7.9–22                  | 18.6 ± 17.9                  | 14.4 ± 14.6                  |
| RSGC1            | 14             | 4.87            | 5.19 ± 0.05     | 14                      | 11.1 ± 11.0                  | 9.0 ± 9.2                    |
| Stevenson 2(RSGC2) | 26             | 4.28            | 4.70 ± 0.06     | 14–20                   | 21.0 ± 20.3                  | 14.1 ± 14.3                  |
| RSGC3*           | 9              | 4.47            | 4.60 ± 0.05     | 16–20                   | 16.8 ± 16.0                  | 15.6 ± 15.5                  |
| Alicante 8 (RSGC4)* | 8              | 4.34            | 4.58 ± 0.06     | 16–20                   | 19.5 ± 18.9                  | 15.9 ± 16.0                  |
| Alicante 7*      | 7              | 3.81            | 4.29 ± 0.13     | –                      | 39.9 ± 39.7                  | 23.2 ± 23.7                  |
| Alicante 10*     | 4              | 4.1             | 4.26 ± 0.09     | –                      | 26.2 ± 25.4                  | 24.2 ± 24.2                  |
| Hodge 301        | 4              | 4.46            | 4.70 ± 0.11     | 3–24                    | 18.4 ± 17.8                  | 15.7 ± 15.4                  |
| SL 639           | 4              | 4.54            | 4.77 ± 0.11     | 7–22                    | 16.9 ± 16.3                  | 14.7 ± 14.4                  |
| NGC 2004         | 6              | 4.35            | 4.67 ± 0.12     | 6.3–24                  | 21.1 ± 19.9                  | 16.2 ± 16.0                  |
| NGC 2100         | 18             | 4.43            | 4.64 ± 0.05     | 7.1–22                  | 19.1 ± 18.3                  | 16.7 ± 16.4                  |
| NGC 1818         | 13             | 3.803           | 4.14 ± 0.06     | 25                     | 45.6 ± 46.2                  | 32.5 ± 32.8                  |
| NGC 330          | 14             | 3.642           | 4.20 ± 0.07     | 32                     | 63.5 ± 63.9                  | 31.4 ± 31.3                  |

Figure 2. Comparison of the ages of the star clusters listed in Table 1 using either the minimum luminosity RSG (diamonds) or the mean RSG luminosity (triangles), derived using single star BPASS models (black) or the binary star BPASS models (red).
MIST models. These shapes of the relations will be dependent on the assumptions assumed in the MIST stellar models (Dotter 2016), most likely at stellar masses below 20 $M_\odot$. The BPASS relations are smoother as these models use consistent physical and numerical ingredients used over the full mass range of the BPASS models.

One effect that we have not considered in detail is stellar rotation. Beasor et al. (2019) did consider how this affected the ages derived from the minimum luminosity RSG. They found that the ages of rotating models could be higher than non-rotating models by as much as 10 per cent. Stellar rotation extends the main-sequence lifetime by mixing in fresh hydrogen into the core during the main sequence. Furthermore, with binary populations, the situation is made complex due to the fact that the most rapidly rotating stars arise from binary interactions (de Mink et al. 2013). Importantly, not every RSG we observe in a population is likely to be a star that had rotated rapidly enough to affect its evolution. Therefore, by using the mean luminosity of all RSGs in a population, possible biasing of the age, due to the lowest luminosity RSG being the product of a rapidly rotating star, is reduced. Given the small difference in ages found by Beasor et al. (2019) compared to the typical uncertainties we find from the distribution of RSG luminosities in our population, we suggest that rotation should not be an important factor in deriving ages from the mean RSG luminosity.

Given our findings, we conclude that the best method to use RSGs to estimate the age of a star cluster is to use all the observed RSGs in a cluster to estimate the mean RSG luminosity. BPASS results indicate that the difference between the mean luminosity for a single star only and that for a realistic binary star population is to within 0.05 dex over a significant age range. Therefore, the estimated age is only weakly dependent on the inherent binary population of a star cluster as postulated by Beasor et al. (2019) and Britavskiy et al. (2019).

Table S1 in the Supporting Information provides our derived mean RSG luminosities from our BPASS models, so others can easily use this method to derive the ages of star clusters. The future uses of such a method are many. First, by constraining the age of the star cluster from the RSGs, the turn-off stars can be examined in detail. Specifically, it can be estimated how many stars are beyond the turn-off expected for a single star population and thus how the interacting binary population and stellar rotation alter the turn-off appearance. Secondly, the stellar populations around some supernova progenitors can also have their age estimated accurately. By using all coeval RSGs alone, rather than the apparent main-sequence turn-off, a significantly tighter age and thus initial mass constrains could be achieved.

ACKNOWLEDGEMENTS

The authors thank the referee for useful feedback that improved the clarity of the paper. The authors thank Héloise Stevance and Max Briel for proofreading of the manuscript. JJE acknowledges travel funding and support from the University of Auckland. Support for this work was provided by National Aeronautics and Space Administration (NASA) through Hubble Fellowship grant HST-HF2-51428 awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA, under contract NAS5-26555. NB acknowledges support from the Spanish Government Ministerio de Ciencia, Innovación y Universidades through grant PGC-2018-0913741-B-C22 and from the Canarian Agency for Research, Innovation and Information Society (ACIISI), of the Canary Islands Government, and the European Regional Development Fund (ERDF), under grant with reference ProID2017010115.

REFERENCES

Beasor E. R., Davies B., Smith N., Bastian N., 2019, MNRAS, 486, 266
Beasor E. R., Davies B., Smith N., van Loon J. T., Gehrz R. D., Figer D. F., 2020, MNRAS, 492, 5994
Britavskiy N. et al., 2019, A&A, 624, A128
Clark J. S. et al., 2009, A&A, 498, 109C
Currie T. et al., 2010, ApJS, 186, 191
de Mink S. E., Langer N., Izzard R. G., Sana H., de Koter A., 2013, A&A, 624, A128
Currie T. et al., 2010, ApJS, 186, 191
Clay J. et al., 2010, A&A, 624, A128
Clark J. S. et al., 2009, A&A, 498, 109C
Currie T. et al., 2010, ApJS, 186, 191
de Mink S. E., Langer N., Izzard R. G., Sana H., de Koter A., 2013, ApJ, 764, 166
Dotter A., 2016, ApJS, 222, 8D
Eldridge J. J., Stanway E. R., Xiao L., McClelland L. A. S., Taylor G., Ng M., Greis S. M. L., Bray J. C., 2017, Publ. Astron. Soc. Aust., 34, 58E
Eldridge J. J., Guo N. -Y ., Rodrigues N., Stanway E. R., Xiao L., 2019, Publ. Astron. Soc. Aust., 36, 41E
Georgy C. et al., 2019, A&A, 622, A66
SUPPORTING INFORMATION

Supplementary data are available at MNRASL online.

Table S1. BPASS estimates for the minimum, mean, and maximum luminosities for stellar populations with metallicity of $Z = 0.020$, 0.008, and 0.004.

Please note: Oxford University Press is not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

This paper has been typeset from a TEX/LATEX file prepared by the author.