



LJMU Research Online

Bastian, N, Niederhofer, F, Kozhurina-Platais, V, Salaris, M, Larsen, S, Cabrera-Ziri, I, Cordero, M, Ekstrom, S, Geisler, D, Georgy, C, Hilker, M, Kacharov, N, Li, C, Mackey, D, Mucciarelli, A and Platais, I

A young cluster with an extended main-sequence turnoff: Confirmation of a prediction of the stellar rotation scenario

<http://researchonline.ljmu.ac.uk/id/eprint/3958/>

Article

Citation (please note it is advisable to refer to the publisher's version if you intend to cite from this work)

Bastian, N, Niederhofer, F, Kozhurina-Platais, V, Salaris, M, Larsen, S, Cabrera-Ziri, I, Cordero, M, Ekstrom, S, Geisler, D, Georgy, C, Hilker, M, Kacharov, N, Li, C, Mackey, D, Mucciarelli, A and Platais, I (2016) A young cluster with an extended main-sequence turnoff: Confirmation of a

LJMU has developed **LJMU Research Online** for users to access the research output of the University more effectively. Copyright © and Moral Rights for the papers on this site are retained by the individual authors and/or other copyright owners. Users may download and/or print one copy of any article(s) in LJMU Research Online to facilitate their private study or for non-commercial research. You may not engage in further distribution of the material or use it for any profit-making activities or any commercial gain.

The version presented here may differ from the published version or from the version of the record. Please see the repository URL above for details on accessing the published version and note that access may require a subscription.

For more information please contact researchonline@ljmu.ac.uk

<http://researchonline.ljmu.ac.uk/>

A Young Cluster With an Extended Main Sequence Turnoff: Confirmation of a Prediction of the Stellar Rotation Scenario

N. Bastian¹, F. Niederhofer^{2,3,4}, V. Kozhurina-Platais⁴, M. Salaris¹, S. Larsen⁵, I. Cabrera-Ziri^{1,6}, M. Cordero⁷, S. Ekström⁸, D. Geisler⁹, C. Georgy⁸, M. Hilker⁶, N. Kacharov¹⁰, C. Li¹¹, D. Mackey¹², A. Mucciarelli¹³, I. Platais¹⁴

¹*Astrophysics Research Institute, Liverpool John Moores University, 146 Brownlow Hill, Liverpool L3 5RF, UK*

²*Excellence Cluster Origin and Structure of the Universe, Boltzmannstr. 2, D-85748 Garching bei München, Germany*

³*Universitäts-Sternwarte München, Scheinerstraße 1, D-81679 München, Germany*

⁴*Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA*

⁵*Department of Astrophysics/IMAPP, Radboud University, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands*

⁶*European Southern Observatory, Karl-Schwarzschild-Straße 2, D-85748 Garching bei München, Germany*

⁷*Astronomisches Rechen-Institut, Zentrum für Astronomie der Universität Heidelberg, Mönchhofstrasse 12-14, D-69120 Heidelberg, Germany.*

⁸*Geneva Observatory, University of Geneva, Maillettes 51, 1290, Sauverny, Switzerland*

⁹*Departamento de Astronomia, Universidad de Concepcion, Casilla 160-C, Chile*

¹⁰*Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany*

¹¹*Department of Physics and Astronomy, Macquarie University, Sydney, NSW 2109, Australia*

¹²*Research School of Astronomy and Astrophysics, Australian National University, Canberra, ACT 2611, Australia*

¹³*Department of Physics and Astronomy, University of Bologna, Viale Berti Pichat 6/2, I-40127 Bologna, Italy*

¹⁴*Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218, USA*

Accepted. Received; in original form

ABSTRACT

We present Hubble Space Telescope photometry of NGC 1850, a ~ 100 Myr, $\sim 10^5 M_{\odot}$ cluster in the Large Magellanic Cloud. The colour magnitude diagram clearly shows the presence of an extended main sequence turnoff (eMSTO). The use of non-rotating stellar isochrones leads to an age spread of ~ 40 Myr. This is in good agreement with the age range expected when the effects of rotation in MSTO stars are wrongly interpreted in terms of age spread. We also do not find evidence for multiple, isolated episodes of star-formation bursts within the cluster, in contradiction to scenarios that invoke actual age spreads to explain the eMSTO phenomenon. NGC 1850 therefore continues the trend of eMSTO clusters where the inferred age spread is proportional to the age of the cluster. While our results confirm a key prediction of the scenario where stellar rotation causes the eMSTO feature, direct measurements of the rotational rate of MSTO stars is required to definitively confirm or refute whether stellar rotation is the origin of the eMSTO phenomenon or if it is due to an as yet undiscovered effect.

Key words: galaxies - star clusters

1 INTRODUCTION

With high precision photometry now regularly accessible with the Advanced Camera for Surveys (ACS) and the Wide Field Camera 3 (WFC3) onboard the Hubble Space Telescope, stellar clusters have been studied in ever increasing detail. This precision has allowed unexpected features in the colour magnitude diagram of young (< 1 Gyr) and intermediate age (1 – 2 Gyr) clusters to be found and studied in detail (e.g., Mackey & Broby Nielsen 2007). One such feature is that the main sequence turn-off (MSTO) of massive

Magellanic Cloud clusters is more extended than expected from a simple stellar population (i.e. a single isochrone) even when including the effects of photometric uncertainties and stellar binarity. The origin of the extended MSTOs (eMSTOs) is still debated in the community.

While age spreads of the order of 200 – 700 Myr appear to be the simplest explanation to the observed MSTO spreads (e.g. Mackey et al. 2008; Milone et al. 2009), such a scenario makes basic predictions that are at odds with observations. The first is that massive clusters should show on-

going star-formation for the first few hundred Myr of their lives, whereas no clusters with ages beyond 10 Myr have been found with active star-formation (Bastian et al. 2013, Cabrera-Ziri et al. 2014; 2016a; Niederhofer et al. 2015a). Moreover, In order to form a second generation of stars, clusters must be able to retain and/or accrete material from their surroundings (e.g., Conroy & Spergel 2011). However, clusters appear to be gas free after 2 – 3 Myr, independent of their masses from $\sim 10^4 - \sim 10^7 M_{\odot}$ (Bastian, Hollyhead, Cabrera-Ziri 2014; Hollyhead et al. 2015) and remain gas free for at least the next few hundred Myr (Bastian & Strader 2014; Cabrera-Ziri et al. 2015; Longmore 2015).

An alternative explanation for the eMSTO phenomenon is that stellar rotation, which affects both the observational properties of the stars as well as their lifetimes through rotational mixing, can cause the spreads (Bastian & de Mink 2009). While initial works cast doubt on this mechanism (Girardi et al. 2011), stellar models that include rotation have been developed in recent years (e.g., Ekström et al. 2012, Georgy et al. 2013) which can be directly compared against observations. Such comparisons have been done for intermediate age clusters (Brandt & Huang 2015a,b) and it seems that for realistic rotational distributions (like those observed in open clusters - Huang et al. 2010) extended MSTOs are expected to be a common feature. Niederhofer et al. (2015b - hereafter N15b) extended this analysis to younger clusters (< 300 Myr) and used the SYCLIST models (Georgy et al. 2014) to investigate the role of stellar rotation in affecting the MSTO¹. They found that if a rotational distribution is present, but is interpreted incorrectly as an age spread, then the inferred age spread is proportional to the cluster age, with younger clusters showing smaller spreads. Additionally, the models predict that, due to rotational mixing, there should be large ($\gtrsim 0.5$ dex) star-to-star [N/H] variations that should correlate with position in the CMD.

N15b compared these predictions to observations of young and intermediate age clusters and found excellent agreement, with the inferred age spread expected to be $\sim 30 - 40\%$ of the age of the clusters. The predictions nicely fit the observations of the young massive cluster NGC 1856 (~ 300 Myr), as interpreted by Milone et al. (2015) and Correnti et al. (2015). One of the predictions of this interpretation is that if younger clusters were studied in the same way, that their inferred age spreads would be correspondingly shorter.

An excellent candidate to test this theory is NGC 1850, a ~ 100 Myr, $2 \times 10^5 M_{\odot}$ cluster in the Large Magellanic Cloud (Fischer et al. 1993; Niederhofer et al. 2015a). If the rotational scenario is correct, then this cluster is expected to host an extended main sequence with an inferred age spread of 30 – 40 Myr. If the eMSTO phenomenon is caused by actual age spreads, due to for example its high escape velocity (e.g., Goudfrooij et al. 2014) then this cluster would be expected to show clear evidence of multiple bursts and/or a continuous star-formation history over its lifetime. In the present work we use new Hubble Space Telescope observa-

tions to study the MSTO of NGC 1850 and compare it to predictions of the rotational scenario and the age spread scenario. The paper is organised as follows: in § 2 we present the observations and analysis tools used while in § 3 we search for spreads in the MSTO and compare it to expectations. In § 4 we discuss our results and present our conclusions.

2 OBSERVATIONS AND DATA REDUCTION

NGC 1850 was observed as part of GO-14069 (PI-N. Bastian) with WFC3/UVIS camera onboard the Hubble Space Telescope through the F336W, F343N and F438W filters with long, intermediate and short exposures. Photometry was carried out on the WFC3/UVIS images that were corrected for the imperfect CTE and simultaneously calibrated for bias, dark, low-frequency flats and the most recent UVIS zero-points (Rayn et al. in preparation). Stellar photometry was derived with PSF fitting, using the spatially variable “effective PSF” (ePSF) method (private communications, J. Anderson), with routines similar to that of ACS/WFC (Anderson & van der Marel 2010). The stellar positions were corrected for the WFC3/UVIS distortion (Bellini et al. 2011). Zeropoints were taken from the STScI website and aperture corrections were derived using isolated stars in the images. More details regarding the photometry will be given in a forthcoming paper (Niederhofer et al. in prep.).

In order to subtract the background field stars, we followed the same procedure as used in Niederhofer et al. (2015a, 2016). We adopt a cluster field, centred on the cluster, with a radius of $2 * r_c$ (where $r_c = 11.1''$ - McLaughlin & van der Marel 2005), and a reference field located near the edge of the images (i.e. as far from the cluster as possible) with the same area as the cluster field. After defining the cluster and the reference field, we constructed CMDs for both fields. For every star in the reference field CMD, we removed the star in the cluster CMD that is closest to the reference field star in colour/magnitude space. After extensive testing we found that this method better removes stellar contamination than applying a grid to the cluster/reference CMDs and subtracting stars from within grid cells. This is discussed in detail in Cabrera-Ziri et al. (2016b).

Additionally, there is a younger cluster, NGC 1850B (~ 5 Myr), nearby our primary target (see Fig. 1), NGC 1850 (Robertson 1974; Gilmozzi et al. 1994). This cluster contributes stars to our ‘cluster CMD’ that were not subtracted based on our background method. In order to remove these stars we defined in a first step an area with a radius of $10''$ centred on NGC1850B and subtracted the background population using a field of the same area that is located opposite of NGC1850 with the same distance from the centre of the main cluster. Then we used this background subtracted field of NGC 1850B to subtract the stars of this younger cluster from our science field.

For the analysis we adopt the BaSTI isochrones² (Pietrinferni et al. 2004, 2006) at $Z = 0.008$ (McLaughlin & van der Marel 2005). The models have scaled solar abundances and include core overshooting. These models do not include stellar rotation.

¹ N15b effectively adopted a spread in rotation rates from $\omega = 0 - 0.5$, where ω is the rotation rate divided by the critical rotation rate, independent of age.

² <http://www.oa-teramo.inaf.it/BASTI>

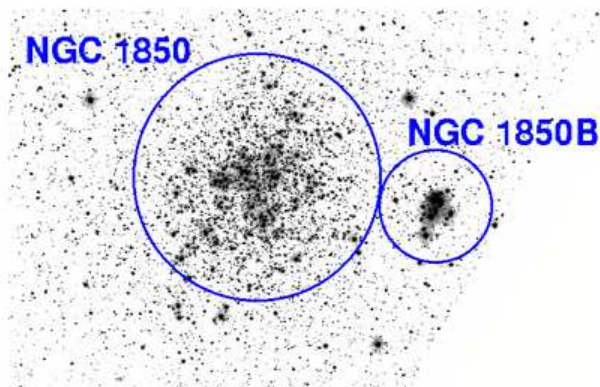


Figure 1. $F438W$ image of NGC 1850 and NGC 1850B. The circles denote the regions used in the present study (22" and 10" for NGC 1850 and 1850B, respectively).

The extinction and distance modulus are found by comparing the isochrones to the shape/location of the main sequence fainter than $F438W = 20$ (i.e. the curve in the lower MS which allows us to break any degeneracies between extinction and distance modulus.). We adopt the same extinction coefficients as Milone et al. (2015), namely $5.10 * E(B - V)$ and $4.18 * E(B - V)$ for the F336W and F438W filters, respectively. We find best fit values of $E(B - V) = 0.1$ and a distance modulus of 18.35, consistent with previous work (e.g., Niederhofer et al. 2015a).

We have estimated the amount of differential extinction in the NGC 1850 field using the technique of Milone et al. (2012). As the extinction vector is largely parallel to the main sequence (MS; $18.5 < F438W < 20.5$) we used the lower part of the MS. While the errors are larger in this region of the CMD, we found no significant differential extinction in the field.

We show the observed, background subtracted, extinction corrected CMD of NGC 1850 in Fig. 2.

In order to estimate the binary fraction within the cluster we created synthetic clusters, based on the BaSTI isochrones and a Salpeter (1955) stellar IMF, with photometric uncertainties taken from the observations. We adopt an age of 100 Myr and a flat mass ratio distribution (in agreement with other works on young massive clusters - e.g., Milone et al. 2015), and only included binaries with $q > 0.5$ (where q is the mass ratio of the secondary to the primary), and varied the binary fraction, $f_{\text{bin}}^{q>0.5}$. We then verticalised the main sequence between $18.5 < F438W < 20.0$ in the observations and synthetic clusters and made a histogram of sources in colour. The histograms were normalised to the same number of stars, and the synthetic cluster most closely resembling the observations was selected. We found the best fit was obtained for $f_{\text{bin}}^{q>0.5} = 0.1 - 0.15$, which if we extrapolate to the full mass ratio distribution leads to $f_{\text{bin}}^{\text{total}} = 0.2 - 0.3$. This synthetic cluster is shown in the right panel of Fig. 2 and we will use it as a comparison cluster in the subsequent analysis.

3 ANALYSIS

As can clearly be seen in the centre panel of Fig. 2, the CMD of NGC 1850 displays a main sequence turn-off that is more extended than would be expected from photometric errors and/or binarity if the underlying population was a simple stellar population. In order to quantify the spread we have carried out two experiments. First, we took a cut across the MSTO, perpendicular to the isochrones and assigned an age to each star in this box based on its proximity to the nearest isochrone. This is similar to what was done in Goudfrooij et al. (2014; hereafter G14), Li et al. (2014; 2016) and Bastian & Niederhofer (2015). The resulting age distribution is shown in Fig. 3 as a histogram. The dashed blue line represents the best fitting Gaussian to the histogram. In order to estimate the intrinsic spread due to photometric errors and binarity, we carried out the same fitting procedure on the synthetic cluster discussed in § 2 and shown in the right panel of Fig. 2. The distribution was then fit with a Gaussian function, which is shown as the red dashed line in Fig. 3.

The MSTO of NGC 1850 is significantly more extended than expected for a single isochrone, including the effects of photometric errors and binarity. The best fitting Gaussian has a dispersion of ~ 20 Myr. The expected dispersion for an SSP (including errors and binarity) is ~ 6 Myr. If we subtract the SSP result from the observational result of NGC 1850 in quadrature, we find that the intrinsic dispersion is 18.9 Myr, corresponding to a FWHM of 44 Myr³.

We have also fit the observed CMD with the star-formation history (SFH) fitting StarFISH package (Harris & Zaritsky 2001), similar to what was done in Niederhofer et al. (2016). We only fit the MSTO portion of the CMD, namely ($14 \leq F336W \leq 19$ and $-1.4 \leq F336W - F438W \leq 0.0$), and we adopted a flat binary distribution with $f_{\text{bin}}^{\text{total}} = 0.25$. The results are shown in Fig. 3 as filled circles and we have normalised the StarFISH distribution to have the same area under the curve as the MSTO distribution. Overall the agreement with the SFH derived from the cut across the MSTO is quite good.

As noted in previous works on the intermediate age clusters (Li et al. 2014; 2016; Niederhofer et al. 2016), the post-main sequence distribution of stars (e.g., the SGB) in some clusters does not appear to be consistent with an age spread within the cluster, instead being narrower and also concentrated towards the 'young' end of the distribution expected from the MSTO (although see Goudfrooij et al. 2015 for an alternative view). The SGB does appear to be narrow in the SYCLIST models including rotation at this age, but this will be investigated in more detail in a future work.

4 DISCUSSION AND CONCLUSIONS

The CMD of NGC 1850 shows evidence for an extended MSTO, similar in nature to that found for the older NGC 1856 (~ 300 Myr; Milone et al. 2015; Correnti et

³ We note that the inferred age spread induced by the photometric uncertainties and binaries is less than the age difference between consecutive isochrones (10 Myr), so the dispersion of 6 Myr is only an estimate. If we would use instead a 10 Myr spread, the corrected eMSTO spread of NGC 1850 would decrease to 40 Myr.

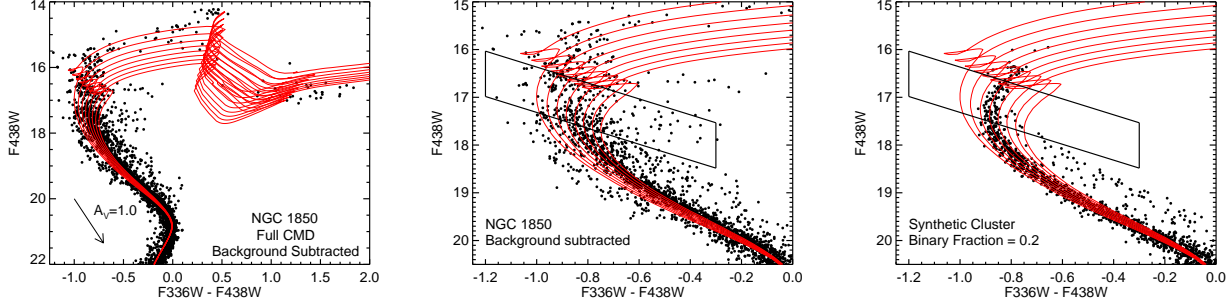


Figure 2. **Left panel:** Field star subtracted colour-magnitude diagram of NGC 1850. We also show the BaSTI isochrones for $Z=0.008$ and a distance modulus of 18.35, for ages between 70 and 140 Myr in steps of 10 Myr. **Middle panel:** A zoom in on the main sequence turn-off (MSTO) portion of the CMD showing that despite the tight lower sequence, the MSTO is clearly extended. **Right panel:** A synthetic cluster with no age spread, errors taken from the observations, a total binary fraction of 20% (flat mass ratio distribution). This simulation was used to determine the expected age spread from binarity and photometric errors. The cut across the MSTO used in the analysis is shown in the middle and right panels.

al. 2015) and the 1 – 2 Gyr intermediate age clusters in the LMC/SMC (e.g., Mackey & Broby Nielsen 2007; G14), however the inferred age spread is significantly smaller than in the other clusters studied to date. In Fig. 4 we show our results for NGC 1850 in the cluster age vs. inferred age spread plane (N15b), shown as a filled star. The points shown, except the YMC Niederhofer et al. (2015a) sample, were all determined in a similar way, i.e. finding the FWHM of the inferred age distribution across the MSTO. NGC 1850 continues the trend reported by Niederhofer et al. (2015b; 2016) that the age spread inferred for young and intermediate age clusters is directly proportional to the age of the cluster itself. N15b predicted that, based on its age of ~ 100 Myr, NGC 1850 should 1) display an extended MSTO and 2) that the inferred age spread (when analysed with non-rotating stellar isochrones) should be ~ 30 Myr, in good agreement with the measured 44 Myr.

The observations presented here are not consistent with the previously suggested interpretation that the eMSTO phenomenon is due to true age spreads within the cluster, as the correlation between cluster age and the inferred age spread is not expected in such a scenario. G14 have suggested a limit in the escape velocity, above which ($\sim 10 - 15$ km/s) clusters can retain the ejecta of AGB stars and form a second generation of stars (this scenario also requires large amounts of gas to be accreted from the surroundings). We note that the lack of abundance spreads within the eMSTO clusters is inconsistent with this scenario (e.g., Mucciarelli et al. 2014). The current escape velocities of many clusters that host MSTO spreads are well below the proposed 10–15 km/s limit (e.g., G14; Milone et al. 2016; Piatto & Bastian 2016), hence G14 assume that clusters begin their lives with much higher masses and escape velocities, and would lose stars due to tidal effects and also the cluster would expand during its lifetime. The assumptions behind this calculation, such as the applicability of the adopted model and the resulting extreme mass loss, have been discussed and questioned elsewhere (Niederhofer et al. 2016; Cabrera-Ziri et al. 2016a).

However we can use NGC 1850 to test this scenario directly. At the age of NGC 1850, in the G14 scenario, the cluster would not have been expected to have lost much of

its initial mass yet, so the derived age distribution should be representative of the initial distribution. Hence, if we applied the G14 scenario to NGC 1850 we would not expect to observe a single Gaussian distribution in age, but rather a large peak when the first generation formed, followed by a smaller (Gaussian) peak due to the formation of the 2nd generation. This is clearly at odds with the observations, which show a single Gaussian type distribution. The same conclusion can be drawn from the observed age distribution of the ~ 300 Myr cluster, NGC 1856 (Milone et al. 2015; Correnti et al. 2015).

The inferred age distribution of NGC 1850, being well approximated by a single (possibly skewed) Gaussian distribution, is the same form seen in the majority of clusters studied to date which host extended MSTOs, although there are notable exceptions, e.g., NGC 1846 (Mackey et al. 2008) and NGC 1783 (Rubele et al. 2013 - although see Niederhofer et al. 2016) which show bi-modal distributions. If stellar rotation is the underlying cause of the eMSTOs, it would imply a specific rotational distribution (potentially bi-modal) for the stars in these clusters (see also D’Antona et al. 2015 and Milone et al. 2016).

Comparison of the observed CMDs of young and intermediate age clusters with stellar models that include rotation (e.g., Brandt & Huang 2015b; N15b; D’Antona et al. 2015) suggest a relatively good agreement between the two, offering support to the notion that stellar rotation is the cause of the eMSTO phenomenon (Bastian & de Mink 2009). However, a definitive test of this scenario will be to measure the rotational velocity ($V_{\text{rot}} \sin(i)$) of a large sample of stars across the eMSTO. This is potentially feasible in the intermediate age clusters, although due to the faintness of the MSTO at this age in the LMC/SMC this will push current instrumentation to its limits. On the other hand, younger clusters such as NGC 1850 and NGC 1856, offer an excellent chance to obtain rotational velocities for large samples of stars along the MSTO due to their increased brightness at this age. Another crucial test of the rotational scenario will be to measure chemical abundances of stars across the MSTO, which are expected to be affected by rotational mixing, especially $[N/H]$ (e.g., Georgy et al. 2013).

In summary, NGC 1850 is another young massive clus-

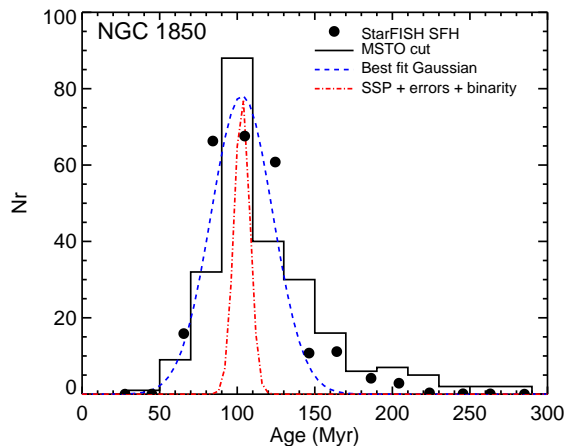


Figure 3. The inferred age spread across the MSTO of NGC 1850. The histogram shows the observed distribution (see text for details) whereas the blue dashed line shows the best Gaussian fit to the data. The red dashed line (narrower distribution) shows the expected spread due to photometric errors and stellar binarity.

ter that hosts an extended main sequence turn-off. If the eMSTO is interpreted as an age spread, based on non-rotating stellar models, the inferred age spread is ~ 40 Myr. This is in good agreement with predictions of the rotational scenario, i.e., if a spread due to a distribution of rotation rates (like that observed in open clusters - Huang et al. 2010) was misinterpreted as an age spread (Niederhofer et al. 2016). The inferred age distribution is also not in agreement with the scenario of actual age spreads put forward by G14, as in such a case the inferred age spread would be expected to be made up of two separate star-formation events, instead of the single smooth Gaussian type distribution found here.

ACKNOWLEDGMENTS

NB gratefully acknowledges financial support from the Royal Society (University Research Fellowship) and the European Research Council (ERC-CoG-646928, Multi-Pop). D.G. gratefully acknowledges support from the Chilean BASAL Centro de Excelencia en Astrofísica y Tecnologías Afines (CATA) grant PFB-06/2007. Support for this project was provided by NASA through grant HST-GO-14069 from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS526555.

REFERENCES

Anderson, J., & van der Marel, R. P. 2010, *ApJ*, 710, 1032
 Bastian, N., & de Mink, S. E. 2009, *MNRAS*, 398, L11
 Bastian, N., Cabrera-Ziri, I., Davies, B., & Larsen, S. S. 2013, *MNRAS*, 436, 2852
 Bastian, N., & Strader, J. 2014, *MNRAS*, 443, 3594
 Bastian, N., Hollyhead, K., & Cabrera-Ziri, I. 2014, *MNRAS*, 445, 378
 Bastian, N., & Niederhofer, F. 2015, *MNRAS*, 448, 1863
 Baumgardt, H., & Makino, J. 2003, *MNRAS*, 340, 227
 Bellini, A., Anderson, J., & Bedin, L. R. 2011, *PASP*, 123, 622
 Brandt, T. D., & Huang, C. X. 2015a, *ApJ*, 807, 24
 Brandt, T. D., & Huang, C. X. 2015b, *ApJ*, 807, 25

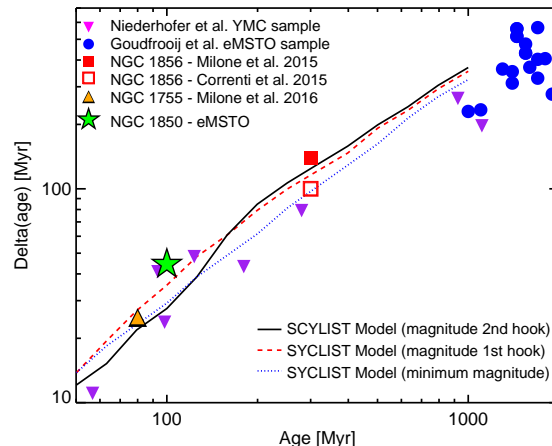


Figure 4. The inferred age spread in a sample of YMCs and intermediate age clusters. NGC 1850, based on the extended MSTO, is shown as a star. We also show predictions from the Geneva models with rotation (Georgy et al. 2013) of the inferred age spread expected if a rotational spread is mis-interpreted as an age spread. Note the strong correlation between the age of the cluster and the inferred age spread, in good agreement with the model predictions. Adapted from N15b.

Cabrera-Ziri, I., Bastian, N., Davies, B., et al. 2014, *MNRAS*, 441, 2754
 Cabrera-Ziri, I., Bastian, N., Longmore, S. N., et al. 2015, *MNRAS*, 448, 2224
 Cabrera-Ziri, I., Bastian, N., Hilker, M., et al. 2016a, *MNRAS*, 457, 809
 Cabrera-Ziri, I. et al. 2016b, *MNRAS*, submitted
 Conroy, C., & Spergel, D. N. 2011, *ApJ*, 726, 36
 Correnti, M., Goudfrooij, P., Puzia, T. H., de Mink, S. E. 2015, *MNRAS*, 450, 3054
 D’Antona, F., Di Criscienzo, M., Decressin, T., et al. 2015, *MNRAS*, 453, 2637
 Ekström, S., Georgy, C., Eggenberger et al. 2012, *A&A*, 537, A146
 Fischer, P., Welch, D. L., & Mateo, M. 1993, *AJ*, 105, 938
 Georgy, C., Ekström, S., Granada, A. et al. 2013, *A&A*, 553, A24
 Georgy, C., Granada, A., Ekström, S., et al. 2014, *A&A*, 566, 21
 Gilmozzi, R., Kinney, E. K., Ewald, S. P., Panagia, N., & Romaniello, M. 1994, *ApJL*, 435, L43
 Girardi, L., Eggenberger, P., Miglio, A. 2011, *MNRAS*, 412, L103
 Goudfrooij, P., Girardi, L., Kozhurina-Platais, V., et al. 2014, *ApJ*, 797, 35
 Goudfrooij, P., Girardi, L., Rosenfield, P., et al. 2015, *MNRAS*, 450, 1693
 Harris, J., & Zaritsky, D. 2001, *ApJS*, 136, 25
 Hollyhead, K., Bastian, N., Adamo, A., et al. 2015, *MNRAS*, 449, 1106
 Huang, W., Gies, D. R., & McSwain, M. V. 2010, *ApJ*, 722, 605
 Li, C., de Grijs, R., & Deng, L. 2014, *Nature*, 516, 367
 Li, C., et al. 2016, *ApJ*, submitted
 Longmore, S. N. 2015, *MNRAS*, 448, L62
 Mackey, A. D., & Broby Nielsen, P. 2007, *MNRAS*, 379, 151
 Mackey, A. D., Broby Nielsen, P., Ferguson, A. M. N., Richardson, J. C. 2008, *ApJL*, 681, L17
 McLaughlin, D. E., & van der Marel, R. P. 2005, *ApJS*, 161, 304
 Milone, A. P., Bedin, L. R., Piotto, G., & Anderson, J. 2009, *A&A*, 497, 755
 Milone, A. P., Piotto, G., Bedin, L. R., et al. 2012, *A&A*, 540, A16
 Milone, A. P., Bedin, L. R., Piotto, G. et al. 2015, *MNRAS*, 450,

3750

- Milone, A. P., Marino, A. F., D'Antona, F., et al. 2016, MNRAS, in press (arXiv:1603.03493)
- Mucciarelli, A., Dalessandro, E., Ferraro, F. R., Origlia, L., & Lanzoni, B. 2014, ApJL, 793, L6
- Niederhofer, F., Hilker, M., Bastian, N., Silva-Villa, E. 2015a, A&A, 575, 62
- Niederhofer, F., Georgy, C., Bastian, N., & Ekström, S. 2015b, MNRAS, 453, 2070
- Niederhofer, F., Bastian, N., Kozhurina-Platais, V., et al. 2016, A&A, 586, A148
- Piatti, A. E., & Bastian, N. 2016, A&A, in press (arXiv:1603.06891)
- Pietrinferni, A., Cassisi, S., Salaris, M., & Castelli, F. 2004, ApJ, 612, 168
- Pietrinferni, A., Cassisi, S., Salaris, M., & Castelli, F. 2006, ApJ, 642, 797
- Rayn, R. et al. 2016, WFC3-ISR (Baltimore: STScI)
- Robertson, J. W. 1974, A&AS, 15, 261
- Rubele, S., Girardi, L., Kozhurina-Platais, V., et al. 2013, MNRAS, 430, 2774
- Salpeter, E. E. 1955, ApJ, 121, 161

This paper has been typeset from a \TeX / \LaTeX file prepared by the author.