The Ages of Stars
Proceedings IAU Symposium No. 258, 2008
E.E. Mamajek, D.R. Soderblom & R.F.G. Wyse, eds.

doi:10.1017/S1743921309031925

The star clusters of the Magellanic Clouds

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Abstract. The Magellanic Clouds possess extensive systems of rich star clusters. These objects span a wide range in age and metal abundance, and are close enough to be fully resolved into individual stars. They represent the most accessible examples of such clusters and are therefore key to a wide variety of astronomical research. In this contribution I describe recent results from work on several problems in Magellanic Cloud cluster astronomy of relevance to *The Ages of Stars*. These include testing and constraining stellar evolution and simple stellar population models, investigating the formation and evolution of the Clouds themselves, and the discovery of several intermediate-age clusters which apparently possess more than one stellar population.

Keywords. Magellanic Clouds, galaxies: individual (Large Magellanic Cloud, Small Magellanic Cloud), galaxies: star clusters, galaxies: formation, galaxies: evolution

1. Introduction

The Large and Small Magellanic Clouds (LMC/SMC) are two dwarf irregular companions to the Milky Way, lying at distances of ~ 50 kpc and ~ 60 kpc, respectively. Both galaxies possess extensive systems of star clusters – the most recent census, by Bica *et al.* (2008), lists over 3700 such objects in total. A significant number of these (perhaps $\sim 100-200$) are rich star clusters with masses comparable to many of the globular clusters observed in the Milky Way. Unlike the Galactic globular clusters, however, Magellanic Cloud clusters have ages spanning the full range $\sim 10^6-10^{10}$ years: from very newly formed objects such as 30 Doradus, to clusters apparently coeval with the oldest Galactic globulars. In addition, the Magellanic Cloud clusters span roughly ~ 2 dex in metal abundance, and are sufficiently close that, with some effort, they may be studied on a star-by-star basis as fully-resolved systems. Taken together, these properties mean that Magellanic Cloud star clusters probe regions of parameter space (in age, metallicity and mass) that are not accessible in such detail anywhere else, and they are hence important to a surprisingly wide variety of astrophysical research (see e.g., Santiago 2009).

In the context of this meeting, there are two key questions we can ask – first, what can we learn from star clusters in the LMC and SMC about how to measure the ages of stars and star clusters; and second, assuming we are able to determine such ages with sufficient accuracy, what astrophysical questions do these two systems allow us to address? Covering the answers to these questions in detail would be worthy of a symposium (or, at the very least, a workshop) each, and is far beyond the scope of this contribution. Here I will merely touch on a few relevant topics which I, personally, find interesting and important, and which have seen significant recent work.

2. Testing stellar evolution models

Because they cover a wide variety of ages and metallicities, are generally considered as template single stellar populations, and are close enough to be studied as fully-resolved

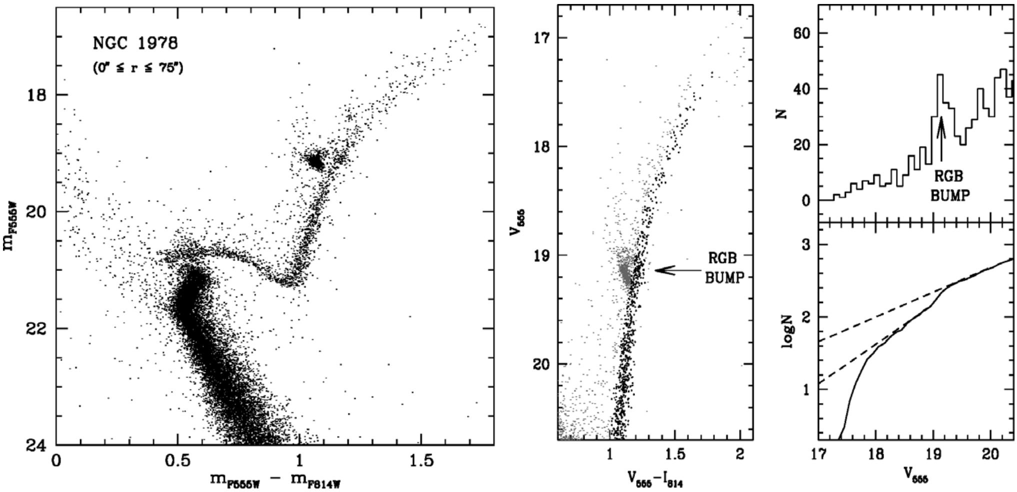

Figure 1. *Left:* CMD constructed from HST/ACS imaging of the rich intermediate-age LMC clusters NGC 1978, taken as part of our snapshot program #9891. The evolutionary sequences are narrow and very well defined. Note that stars brighter than $m_{\rm F555W} \approx 18$ are saturated, so that the upper RGB is artificially broadened. *Centre and Right:* These plots, reproduced from Mucciarelli *et al.* (2007), show the presence of the RGB bump in the cluster CMD. This feature is particularly evident in the luminosity function of the RGB stars, shown at right.

systems, the massive star clusters of the Magellanic Clouds have long been used to progress various aspects of our understanding of stellar evolution, and to test and constrain stellar evolution models. Topics for study have been as wide-ranging as, for example, the properties of variable stars, including Cepheid variables (e.g., Bono & Marconi 1997); the evolutionary properties of high- and intermediate-mass stars (e.g., Massey & Hunter 1998; Barmina *et al.* 2002); the properties of stars undergoing very rapid phases of evolution such as occur on the AGB (e.g., Girardi & Marigo 2007; Lebzelter & Wood 2007; Lebzelter *et al.* 2008); and the properties of pre-main sequence stars (e.g., Nota *et al.* 2006; Carlson *et al.* 2007; Gouliermis *et al.* 2007; Hennekemper *et al.* 2008).

An interesting recent example has been the work done by Mucciarelli *et al.* (2007) on the very rich intermediate-age LMC cluster NGC 1978. This object was imaged with HST/ACS as part of our Cycle 12 snapshot survey of Magellanic Cloud clusters (program #9891, PI: G. Gilmore). The CMD for NGC 1978 is shown in the left panel of Fig. 1. Due to the high photometric accuracy of HST/ACS the evolutionary sequences are narrow and very well defined; further, because of the rather high mass of the cluster (2×10^5 M$_\odot$) these sequences are all very well populated – even for relatively rapid evolutionary phases such as the SGB. Mucciarelli *et al.* (2007) noted the presence of the so-called RGB bump – this occurs at $m_{\rm F555W} \approx 19.10$ (Fig. 1, central panel). To emphasize this feature, Mucciarelli *et al.* (2007) constructed a luminosity function (LF) for the cluster RGB stars (Fig. 1, right panels) – the RGB bump shows up clearly in both the binned and cumulative forms of the LF. Although the RGB bump has been observed in several Galactic globulars, this is the first clear-cut detection of this feature in an intermediate-age cluster.

Mucciarelli *et al.* (2007) compare the observed morphology of the evolutionary sequences with the expectations of stellar evolution models from several groups. Because of their high quality photometry, the authors were able to incorporate both the shape of the cluster CMD and the observed ratios of stars on different evolutionary sequences – for example, the number of RGB stars to the number of SGB stars. These ratios provide

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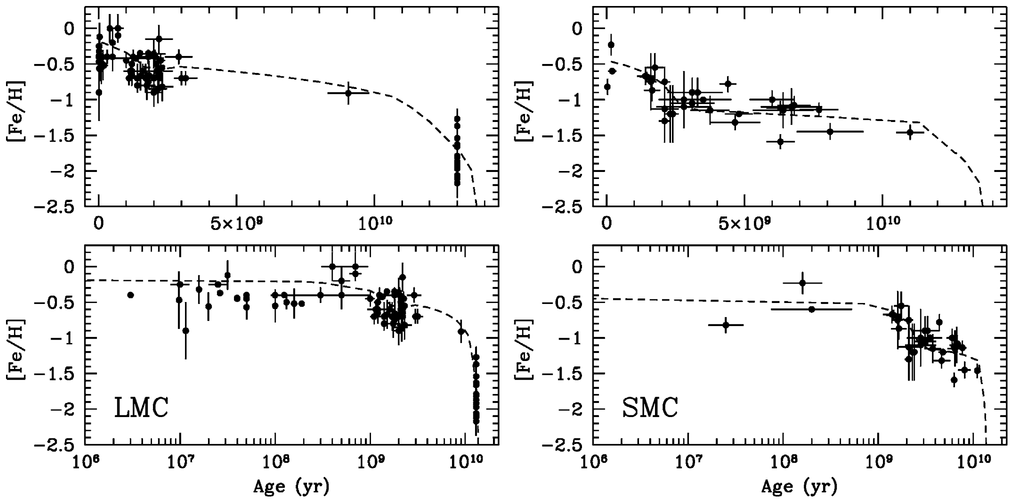

Figure 2. Age-metallicity relationships for clusters in the LMC (left panels) and SMC (right panels). In the upper panels the age axis is plotted linearly; in the lower panels it is plotted logarithmically. All data were assembled from compilations in the recent literature: Geisler *et al.* (2003); Glatt *et al.* (2008a,b); Kerber *et al.* (2007); Mackey & Gilmore (2003a,b); Mackey & Gilmore (2004); Mackey *et al.* (2006); Piatti *et al.* (2003); Piatti *et al.* (2005); Piatti *et al.* (2008); see also the references listed in these works. The dashed lines are chemical enrichment models by Pagel & Tautvaišienė (1998) for bursting star-formation histories.

direct constraints on the evolutionary time-scales. They find that the best-fitting models all require some degree of convective overshooting to properly reproduce both evolutionary sequence morphologies and star counts. Furthermore, none of the models performed particularly well in reproducing the location of the RGB bump. Future observations of this feature in additional clusters may therefore be useful for placing empirical constraints on the evolutionary tracks of intermediate-age stars.

3. Formation and evolution of the Magellanic Clouds

The star cluster systems of the Magellanic Clouds are of considerable importance to our understanding of the formation and evolution of the Clouds themselves. Fig. 2 presents age-metallicity relationships derived from LMC and SMC clusters. There are several notable features in these two plots. Both show a clear increase in metal abundance with time, indicating the process of chemical enrichment in the two Clouds. At any given age (except perhaps for the very oldest objects), the SMC star clusters are on average more metal-poor than those in the LMC, indicating that chemical enrichment processes have proceeded more slowly in the smaller galaxy. Over-plotted are the predictions of chemical enrichment models by Pagel & Tautvaišienė (1998) for bursting star-formation histories in the two Clouds. These do a good job of matching the observed cluster data – better, arguably, than do models for continuous star-formation histories (see also Da Costa & Hatzidimitriou 1998; Piatti *et al.* 2005). One important question is whether the age-metallicity relationships from star clusters match those derived from field stars – that is, can we reliably infer chemical enrichment histories in distant galaxies where the field populations cannot be resolved, by studying the integrated properties of individual star clusters? This is still an unsolved problem; however, the Magellanic Clouds are clearly excellent laboratories for its study, and significant progress is being made (see, e.g., the contribution by Gallart in these proceedings).

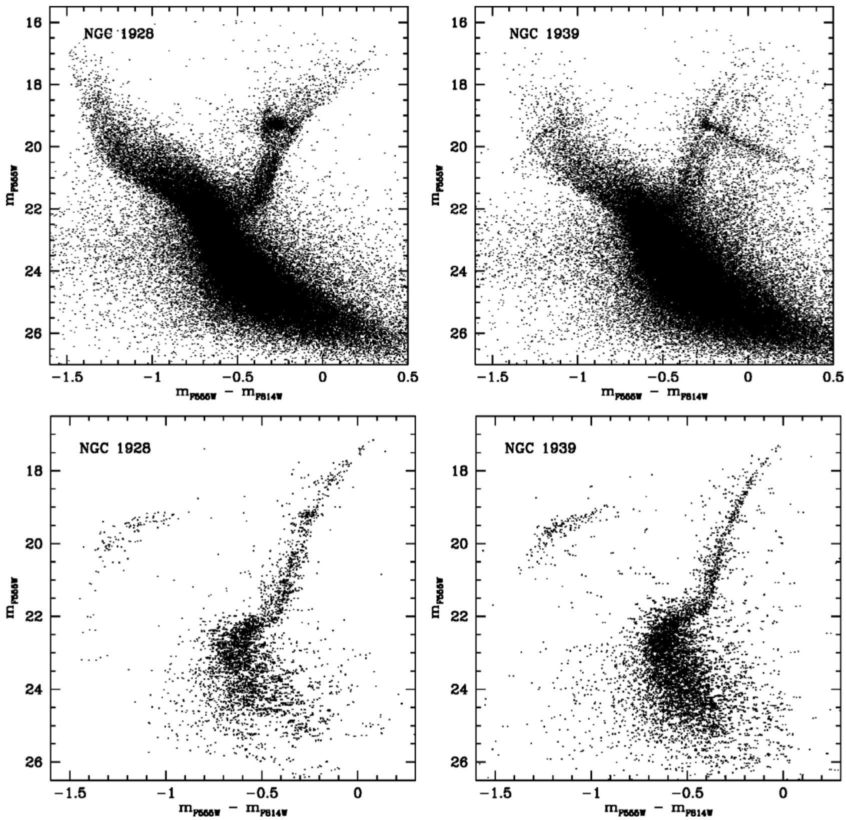

Figure 3. CMDs constructed from HST/ACS observations of the old LMC clusters NGC 1928 (left) and 1939 (right) taken as part of our snapshot program #9891 (Mackey & Gilmore 2004). The upper panels show all stellar detections in the two ACS observations – the LMC bar fields against which the clusters are projected are so densely populated that it is impossible to clearly discern the cluster sequences. Only after a careful statistical subtraction of the field has been made (lower panels) does the ancient nature of the two targets become evident. Comparison of the fiducial sequences for NGC 1928 and 1939 with those for the oldest Galactic and LMC clusters revealed the full group of objects to be coeval within ~ 2 Gyr.

What is certainly clear is that the observed cluster formation history in a galaxy does not necessarily accurately reflect its star formation history. A notable feature of the LMC cluster formation history is an almost complete dearth of clusters with ages in the range $\sim 3 - 13$ Gyr. This "age gap" is quite evident in the upper left panel of Fig. 2, and is a well-known feature of the LMC system (e.g., Jensen *et al.* 1988; Da Costa 1991; Sarajedini 1998; Rich *et al.* 2001). Barring one object (see below), extensive searches have failed to locate any clusters lying in the age gap (e.g., Geisler *et al.* 1997); however, the LMC star-formation rate was clearly non-zero during this period of time (e.g., Holtzman *et al.* 1999; Smecker-Hane *et al.* 2002; Carrera *et al.* 2008). Curiously, the SMC does not appear to have an age gap, as it possesses many intermediate-age star clusters (e.g., Mighell *et al.* 1998; Rich *et al.* 2000; Glatt *et al.* 2008b). The LMC age gap has been interpreted theoretically in terms of repeated tidal interactions between the LMC, SMC, and Milky Way (Bekki *et al.* 2004); however, it is not yet clear how such models can be reconciled with the recent large LMC and SMC proper motions measured with HST (Kallivayalil *et al.* 2006a,b; Besla *et al.* 2007).

The one LMC cluster known to have an age lying in the range $3-13$ Gyr is ESO 121-SC03. This was first studied by Mateo *et al.* (1986), who identified it as an unusual, and possibly unique, LMC member. ESO 121-SC03 was imaged as part of our Cycle 12 HST snapshot survey of rich star clusters in the Magellanic Clouds (program #9891), which has allowed construction of a deep CMD, and precise constraints to be placed on its age. Mackey *et al.* (2006) showed that the CMD of ESO 121-SC03 is very similar to that of the young Galactic globular cluster Palomar 12, which is known to have been accreted from the Sagittarius dwarf galaxy. Mackey *et al.* (2006) further demonstrated that ESO 121-SC03 is $73 \pm 4\%$ as old as the well-studied Galactic globular cluster 47 Tuc (NGC 104). Together these results translate into an age of 9.0 ± 0.8 Gyr, confirming that ESO 121-SC03 is indeed the only known LMC cluster to fall in the age gap.

It is also of interest to consider the oldest clusters in the two Magellanic systems. The LMC in particular possesses a significant population of extremely old objects, with ages ~ 13 Gyr – these clusters form the upper boundary of the age gap. Deep, high-resolution imaging from HST has allowed detailed relative age comparisons between members of this population and the oldest Galactic globular clusters (e.g., Brocato *et al.* 1996; Olsen *et al.* 1998; Johnson *et al.* 1999; Mackey & Gilmore 2004). These studies have shown that, to within the precision of current techniques, the oldest LMC clusters are coeval with the oldest Galactic globulars. Furthermore, there is a dispersion of at most ~ 2 Gyr among the ensemble of ancient LMC clusters. These results imply that the LMC formed at the same time as the Milky Way. There is also a significant spread in iron abundance among the ancient LMC globular clusters (Fig. 2), indicating that, at least in some locations, there must have been rapid early chemical enrichment in this galaxy.

A relevant question is whether the census of ancient LMC clusters is now complete. Some indication of the difficulties involved in answering this question can be seen from Fig. 3, which shows CMDs for the most recently identified members of this population, NGC 1928 and 1939 (Mackey & Gilmore 2004). These two clusters are so compact and lie against such highly crowded LMC bar fields that it required HST/ACS to obtain CMDs definitively proving their age; even then, the task was not straightforward. It is conceivable other such clusters still remain unidentified. Furthermore, a number of the oldest LMC clusters are extremely remote objects – NGC 1841 lies more than 14° from the LMC centre. It is certainly possible that unknown faint, remote old LMC clusters exist; forthcoming surveys should facilitate the discovery of any such objects.

In the SMC the story is somewhat different. There is only one cluster known to be older than 10 Gyr, NGC 121, and several HST-based studies have shown this object to clearly be ~ 2 Gyr younger than the oldest Galactic and LMC globulars (Mighell *et al.* 1998; Shara *et al.* 1998; Glatt *et al.* 2008a). It is not clear what the somewhat young age of NGC 121 tells us about the formation of the SMC – it may be that it results from delayed cluster formation in this galaxy, or it may result from the random survival of only one object out of a small population of ancient clusters. NGC 121 is also not particularly metal-poor, indicating that in the SMC, as in the LMC, there must have been some significant chemical enrichment relatively early on.

4. Integrated light measurements

The massive star clusters of the Magellanic Clouds are extremely useful as calibrators of simple stellar population (SSP) models, because they span a wide variety of ages and metal abundances, and, in addition, because they are located at a very convenient distance where precise observations of both their integrated and resolved properties may be obtained. With such measurements in hand, accurate ages and metallicities derived from

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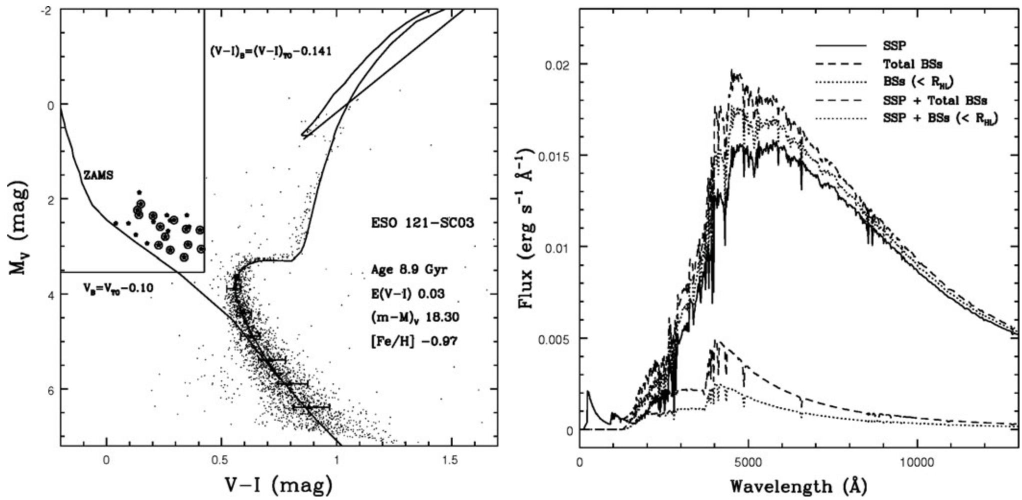

Figure 4. *Left:* A HST/ACS CMD for the LMC age gap cluster ESO 121-SC03. The significant population of blue straggler stars in this cluster is highlighted. *Right:* The effect of these stars on the cluster's integrated spectral energy distribution (ISED) is illustrated. The solid line is the ISED from the SSP model of appropriate age and metallicity. The dotted lines show the expected contribution to the ISED made by blue stragglers within the cluster half-light radius; while the dashed lines show the expected contribution made by all blue stragglers thought to be cluster members. The effect of the blue stragglers is quite significant, especially blueward of ~ 7000Å. These plots have been reproduced from Xin *et al.* (2008).

the resolved observations may be compared to the predictions of evolutionary synthesis models derived from, for example, the integrated cluster colours observed in different pass-bands. Providing empirical tests and constraints on SSP models in this way is of significant importance, because in galaxies beyond the Local Group it is at present not possible to resolve clusters into individual stars – therefore, information on cluster ages and metal abundances may only be obtained from integrated light measurements. An interesting example of this process is the recent work of Pessev *et al.* (2006, 2008), who assembled a database of near-infrared and optical integrated colours for a large sample of massive Magellanic Cloud clusters, and then used this information in combination with the known ages and metallicities of these objects (as derived from resolved photometry and spectroscopy) to test the performance of four popular SSP models in optical/near-IR colour-colour space.

One hitherto poorly-investigated aspect of the above problem is the effect of stars which are not well-incorporated into SSP models on the properties derived from integrated measurements. For example, blue stragglers are found in many different types of star cluster; however, such objects are not included in SSP models because they are generally formed as the result of binary star evolution or stellar dynamical processes. The presence of such stars in a cluster can add a significant contribution to the integrated light at blue and ultraviolet wavelengths, especially in older clusters where the stars are generally quite red, and this can lead to significant errors when deriving ages and metallicities from SSP models – specifically, the derived cluster age will be too young and the derived metal abundance too low†. As a demonstration of this problem, Xin *et al.* (2008) studied the LMC age gap cluster ESO 121-SC03, which possesses a significant population of blue stragglers (Fig. 4). They showed that these stars can make a significant alteration

† Note that a similar role can be played by extreme blue horizontal branch stars in very old clusters – the parameters controlling horizontal branch morphology are still not fully understood, and therefore not well-incorporated into SSP models.

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to the derived broad-band integrated colours of the cluster, as well as to its integrated spectral energy distribution. These can lead to an age underestimate of $\sim 40-60\%$ and a metallicity underestimate of $\sim 30-60\%$. Ultimately, by assessing such effects over a wide variety of cluster ages, metallicities and dynamical environments, it should be possible to derive empirical corrections for SSP models to account for the effects of blue stragglers. Magellanic Cloud clusters will certainly play a significant role in achieving this goal.

5. Multiple stellar populations in Magellanic Cloud clusters

Recent photometric studies of massive intermediate-age star clusters in the Magellanic Clouds have discovered objects exhibiting extremely unusual main-sequence turn-offs (MSTOs) in their CMDs. The first indications that such clusters might exist date back several years to observations obtained with terrestrial facilities – Bertelli *et al.* (2003) demonstrated that the LMC cluster NGC 2173 apparently possesses an unusually large spread in colour about its MSTO, while Baume *et al.* (2007) obtained a similar result for the LMC cluster NGC 2154.

More recent studies based on deep precision photometry from HST/ACS have revealed the truly peculiar nature of many intermediate-age LMC clusters. The clearest example is NGC 1846, which was first imaged as part of our Cycle 12 snapshot survey of rich star clusters in the Magellanic Clouds (program #9891). The CMD for this cluster displays two distinct MSTO branches (Mackey & Broby Nielsen 2007), but is otherwise as expected for an intermediate-age cluster. In particular, it possesses a narrow red-giant branch, sub-giant branch and main sequence, and a compact, well-defined red clump (Fig. 5). This implies that the turn-off features are not due to significant line-of-sight depth or differential reddening in this cluster. The narrow sequences further suggest a minimal internal dispersion in [Fe/H]; however, they do not allow strong constraints to be placed on the possibility of internal variations in other chemical abundances – for example, CN, O, Na, or [α/Fe] – as are observed for several of the peculiar massive Galactic globular clusters (e.g., Piotto *et al.* 2008).

Our Cycle 12 snapshot data revealed several additional candidates possessing unusual MSTOs – for example, NGC 1806, 1783, 1852, and 2154, in decreasing order of significance. CMDs for these clusters are presented in Mackey *et al.* (2009); our result for NGC 2154 apparently confirms the observations of Baume *et al.* (2007). Three of the most populous clusters in our sample of candidates, NGC 1846, 1806, and 1783, have deeper ACS imaging available in the HST public archive – this is from GO program #10595 (PI: P. Goudfrooij). Several groups have independently recently published CMDs from these data (Mackey *et al.* 2008; Milone *et al.* 2008; Goudfrooij *et al.* 2009) – each group used different photometry software but the CMDs match quite closely (although differing in some fine details). In Fig. 6 I present the results from Mackey *et al.* (2008). Each of the three clusters unambiguously possesses a peculiar MSTO: NGC 1846 and 1806 possess two MSTO branches, while NGC 1783 possesses a turn-off covering a spread in colour much larger than can be explained by the photometric uncertainties (note the very narrow upper main sequence). This feature may represent a bifurcated turn-off in which the branches are unresolved on the CMD (see e.g., Milone *et al.* 2008), or it may represent a smooth spread of stars.

As with NGC 1846, both NGC 1806 and 1783 possess very narrow sequences across the remainder of their CMDs, implying no significant line-of-sight depth, differential reddening, or internal dispersion in [Fe/H] for either of these two systems. Mucciarelli *et al.* (2008) obtained high resolution spectra for 6 RGB stars in NGC 1783 and found no significant star-to-star dispersion in [α/Fe]; however similar measurements are not presently available for NGC 1846 or 1806. If, in the absence of this information, we assume

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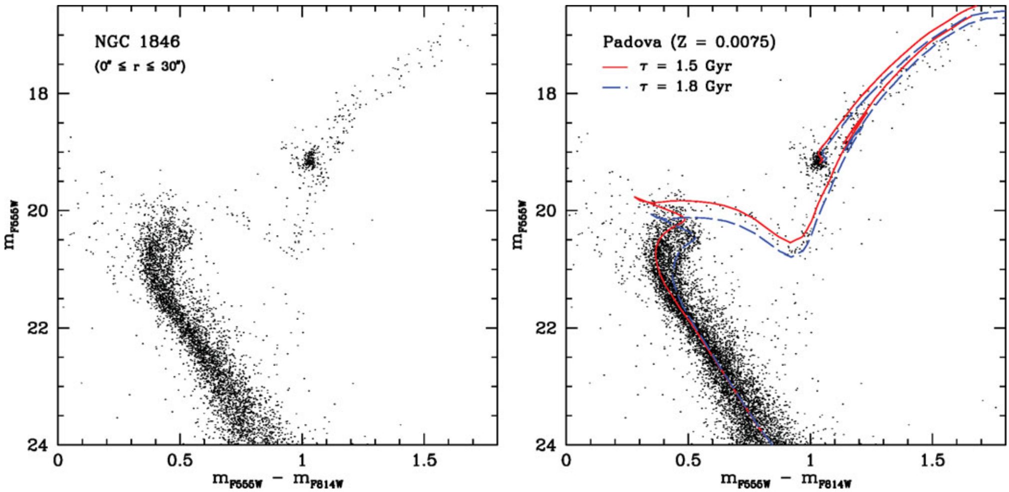

Figure 5. *Left:* HST/ACS CMDs from our HST snapshot imaging of NGC 1846. The double main-sequence turn-off is clearly visible (Mackey & Broby Nielsen 2007); otherwise the CMD is as expected for an intermediate-age cluster (see text). *Right:* Isochrone fit to the HST #9891 CMD for NGC 1846. Under the assumption of chemical homogeneity and a uniform distance and foreground extinction, an age spread of $\sim$300 Myr within this $\sim$1.8 Gyr old cluster can closely reproduce the observed CMD.

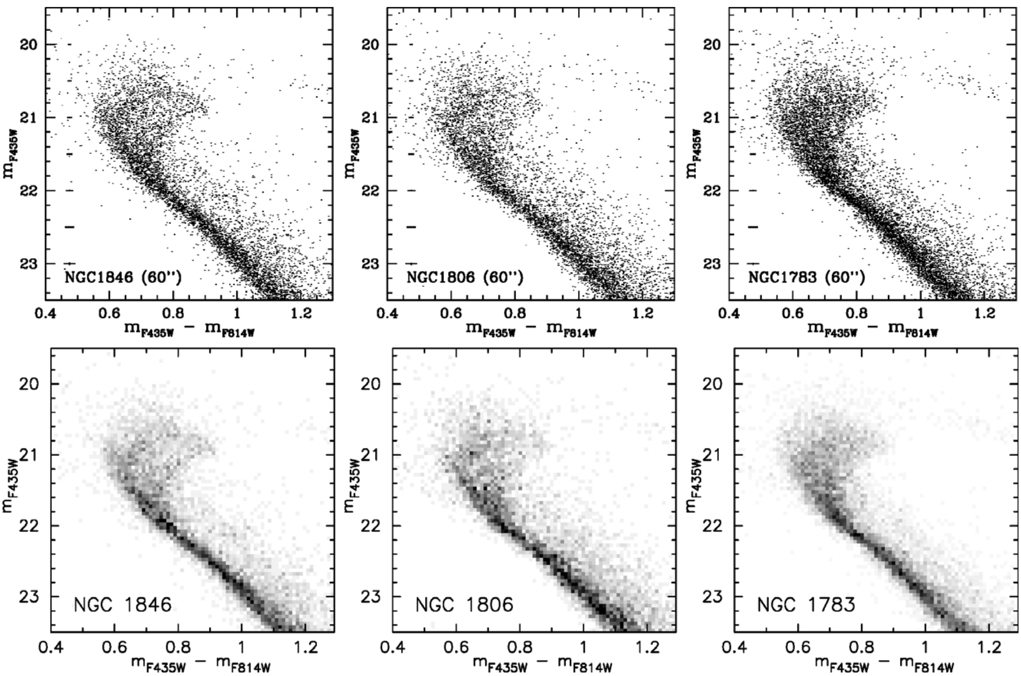

Figure 6. HST/ACS CMDs (upper panels) and Hess diagrams (lower panels) constructed from imaging taken under HST program #10595, obtained from the public archive. These deep CMDs confirm the peculiar nature of the clusters identified in our HST #9891 snapshot imaging. NGC 1846 and 1806 clearly display bifurcated main-sequence turn-offs, while NGC 1783 has a turn-off exhibiting a large spread in colour. Each cluster has a very narrow main sequence and a significant population of unresolved binary stars.

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complete chemical homogeneity in each of the three systems, the simplest explanation for the peculiar MSTOs is that each cluster possesses at least two stellar populations of differing ages. Isochrone fitting (e.g., Fig. 5) results in implied age spreads of $\sim 200-300$ Myr within each cluster, with the oldest populations being $\sim 1.8-2.0$ Gyr old (Mackey & Broby Nielsen 2007; Mackey *et al.* 2008; Milone *et al.* 2008). Note that each of the three clusters possesses a significant population of unresolved binary stars (evident from their CMDs); however, these do not explain the MSTO morphologies (Mackey *et al.* 2008).

Milone *et al.* (2008) studied a large sample of 16 intermediate-age LMC clusters with HST/ACS imaging, and found that 11 of these possess CMDs exhibiting MSTOs which are not consistent with being simple, single stellar populations. Of these 11, four clearly show bifurcated MSTOs (the three described above plus NGC 1751) while the remainder possess more sparsely populated CMDs that make the precise morphologies of their peculiar MSTOs difficult to ascertain. All are consistent with being double TOs, or alternatively with possibly being more smoothly distributed intrinsic broadenings. Nonetheless, all 11 clusters again exhibit narrow sequences across the remainder of their CMDs, suggesting that the peculiar MSTO features are due to internal age dispersions of $\sim 150-300$ Myr. Of their three most populated clusters with double MSTOs, Milone *et al.* (2008) found that the inferred younger populations may comprise up to $\sim 70\%$ of the stars in the central regions of these systems. It is further worth noting that one intermediate-age SMC cluster, NGC 419, also likely possesses a peculiar MSTO (Glatt *et al.* 2008b).

The rapidly-growing number of intermediate-age Magellanic Cloud star clusters that are being found to possess peculiar MSTO morphologies suggests that such a feature may not be uncommon for this type of object. This is a surprising result since, as discussed above, Magellanic Cloud star clusters have long been treated as prototypical single stellar populations, used to test and calibrate stellar evolution and SSP models. A number of possible origins for these peculiar clusters have been proposed – for example, self-pollution by AGB stars; the merger of two (or more) star clusters formed in the same giant molecular cloud (GMC); or a scenario where clusters interact and merge with star-forming GMCs (Bekki & Mackey 2009). One alternative possibility is that the MSTO morphologies represent some hitherto poorly-understood aspect of the evolution of intermediate-age stars. In this case, Magellanic Cloud clusters will, once again, be teaching us something new about stellar evolution.

Acknowledgements

ADM is supported by the Marie Curie Excellence Grant of Annette Ferguson, which comes from the European Commission under contract MCEXT-CT-2005-025869. ADM is grateful to Alessio Mucciarelli and Yu Xin for their kind help with Figures 1 and 4.

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Discussion

S. Yi: The AGB scenarios produce extreme helium populations best if the age separation between the old and young populations is roughly 100 Myr, which is the case with NGC 1846. Do you see a bluer MS for the younger population?

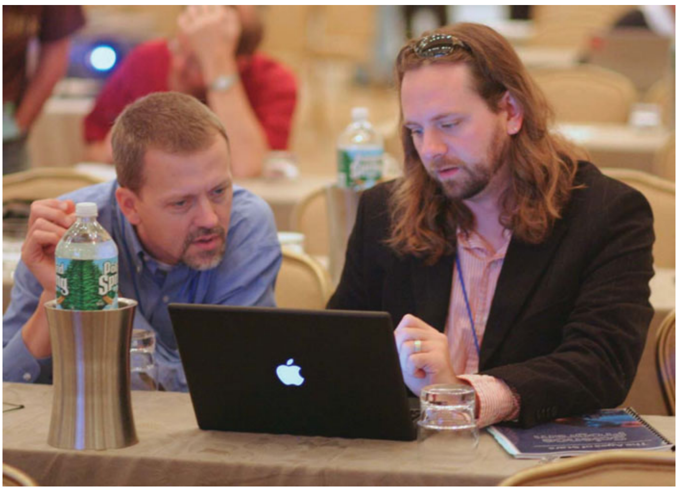
D. Mackey: I've often wondered about that but unfortunately the data we presently have in hand are not sufficiently deep to resolve any split in the main sequence. However, there's no reason why we can't look for this in the future; the required observations are not too tough and it's certainly a vital problem to address.

J. Kalirai: Is there any spatial segregation between the stars in the brighter vs. fainter turnoffs of the LMC clusters? Do you see evidence for mass segregation between the two populations?

D. Mackey: In my original paper on NGC 1846 (Mackey & Broby Nielsen 2007, MNRAS, 379, 151), I looked at this and saw no segregation between the two populations ("young" and "old" turn-off stars). However, another recent study is claiming to see some spatial distinction (P. Goudfrooij, private communication). I'm not sure yet how to reconcile the two results but it would certainly help constrain formation scenarios if we could get a definitive answer.

https://doi.org/10.1017/S1743921309031925 Published online by Cambridge University Press

Doug Mackey



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https://doi.org/10.1017/S1743921309031925 Published online by Cambridge University Press