Star Clusters: From the Milky Way to the Early Universe
Proceedings IAU Symposium No. 351, 2019
A. Bragaglia, M. Davies, A. Sills & E. Vesperini, eds.

doi:10.1017/S1743921319007725

The range of UV upturn strengths in early-type galaxies can be caused by dissolved metal-rich Globular Clusters

Paul Goudfrooij

Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
email: goudfroo@stsci.edu

Abstract. I summarize the scenario by Goudfrooij (2018) in which the bulk of the ultraviolet (UV) upturn of giant early-type galaxies (ETGs) is due to helium-rich stellar populations that formed in massive metal-rich globular clusters (GCs) and subsequently dissolved in the strong tidal field in the central regions of the massive host galaxy. These massive GCs are assumed to show UV upturns similar to those observed recently in M87, the central galaxy in the Virgo cluster of galaxies. Data taken from the literature reveals a strong correlation between the strength of the UV upturn and the specific frequency of metal-rich GCs in ETGs. Adopting a Schechter function parametrization of GC mass functions, simulations of long-term dynamical evolution of GC systems show that this correlation can be explained by variations in the characteristic truncation mass $\mathcal{M}_c$ such that $\mathcal{M}_c$ increases with ETG luminosity in a way that is consistent with observed GC luminosity functions in ETGs. These findings suggest that the nature of the UV upturn in ETGs and the variation of its strength among ETGs are causally related to that of helium-rich populations in massive GCs, rather than intrinsic properties of field stars in ETGs.

Keywords. galaxies: stellar content — galaxies: bulges – galaxies: star clusters: general

1. The Mystery of the UV Upturn in Early-Type Galaxies

A long-standing mystery in the nature of stellar population properties of giant early-type galaxies (ETGs) is their rising flux at ultraviolet wavelengths below ∼2000 Å (Code & Welch 1979), requiring sources with effective temperatures exceeding 20,000 K (Brown *et al.* 1997). This phenomenon is commonly known as the *UV Upturn* of ETGs, which was unexpected at the time since ETGs were thought to be "red and dead" galaxies. After low-level star formation was ruled out as the cause (e.g., Bohlin *et al.* 1985), it is now generally recognized that the bulk of the far-UV flux in ETGs originates from helium-burning extreme horizontal branch (EHB) stars and their progeny (e.g., O'Connell 1999). However, there are two competing scenarios: metal-poor EHB stars (Park & Lee 1997; Buzzoni & González-Lópezlira 2008) and metal-rich EHB stars (e.g., Greggio & Renzini 1990; Yi *et al.* 1997). Since giant ETGs are old metal-rich stellar systems, the metal-rich solution generally seems to be most viable, but the issue is that metal-rich EHB populations can only produce sufficient FUV flux if they have very high Helium abundance (e.g., Chung *et al.* 2017). The big question in the context of the metal-rich scenario is therefore *how giant ETGs could have accumulated such high He abundances.*

Important clues in this context are *(1)* the strong, well-known correlation between the strength of the UV upturn (measured by $m(1550)-V$) and the central velocity dispersion of the galaxy (σ), meaning that the UV upturn is generally strongest for the most massive galaxies (e.g., Bureau *et al.* 2011), and *(2)* the fact that the far-UV emission of early-type

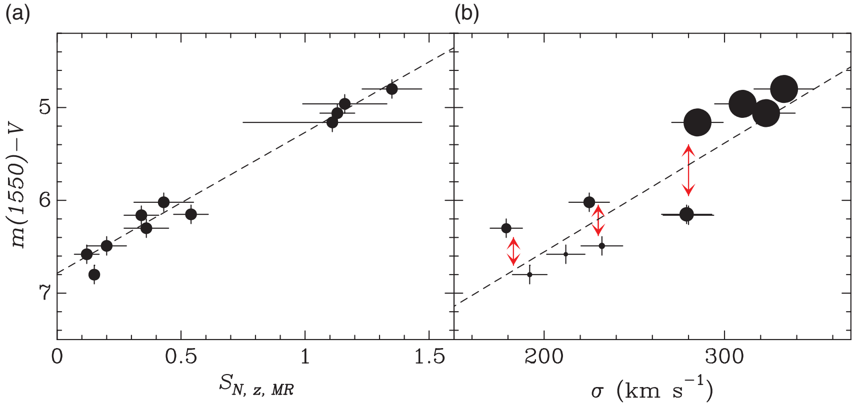

Figure 1. *Panel (a)*: De-reddened FUV upturn strength $m(1550)-V$ versus the specific frequency of metal-rich GCs in the SDSS z band ($S_{N,\,z,\,MR}$) of the galaxies in the sample of Goudfrooij (2018). Note the very strong (anti-)correlation as discussed in the text. *Panel (b)*: $m(1550)-V$ versus central velocity dispersion σ for the same galaxy sample. The symbol size is proportional to $S_{N,\,z,\,MR}$ of the galaxy in question. Note that the scatter in this well-known relation is mainly driven by $S_{N,\,z,\,MR}$, in that galaxies with higher $S_{N,\,z,\,MR}$ have a systematically stronger UV upturn at a given σ. This is further emphasized by the red arrows. Dashed lines in both panels show the best-fit linear relation between the two parameters.

galaxies is much more centrally concentrated than the optical light (e.g., Carter *et al.* 2011). But why would more massive galaxies have accumulated higher He abundances than less massive ones, and why primarily in their inner (very metal-rich) regions?

Interestingly, the only galactic environment where strong He enhancement is *known* to occur is in massive globular clusters (GCs). Recent photometric and spectroscopic observations of GCs have yielded growing evidence that massive GCs cannot be considered "simple stellar populations" any longer, as they appear to show significant internal spreads among light-element abundances (e.g., Bastian & Lardo 2018). Well-known examples of this are the so-called Na-O anticorrelation and the spread of He abundance (ΔY) within a cluster, the extent of both of which correlate strongly with GC mass (Carretta *et al.* 2010; Milone *et al.* 2018). These relations are thought to result from GC self-enrichment by means of winds of "polluter" stars that undergo proton capture reactions at $T \geqslant 10^{7.6}\,K$, facilitating the CNO, Ne-Na, and O-N cycles which produce increased [N/Fe], [Na/Fe] and He abundance Y along with smaller decreases of [O/Fe] and [C/Fe] (e.g., Bastian & Lardo 2018; see also R. Gratton's paper in this volume). The observed GC mass dependence likely reflects the range of abilities of the young GCs to retain the N- and He-enriched wind material of the polluter stars.

With the above in mind, we investigated relations between the UV upturn and properties of the GC systems of ETGs. This proceedings paper summarizes the results of this investigation; a much more detailed description can be found in Goudfrooij (2018).

2. Fueling the UV Upturn by Stars from Massive Metal-Rich GCs

The strongest correlation found by Goudfrooij (2018) was that between UV upturn strength and $S_{N,\,MR}$, the specific frequency of metal-rich GCs. The latter is defined as the number of GCs in the metal-rich (red) peak of the well-known bimodal optical color distribution of GCs in ETGs, normalized by the galaxy luminosity. As shown in Figure 1, *this correlation is very strong and may even be causal* since galaxies with high values of $S_{N,\,MR}$ systematically have stronger UV upturns than those with low values of $S_{N,\,MR}$

https://doi.org/10.1017/S1743921319007725 Published online by Cambridge University Press

in the *m(1550)*−V vs. σ plot.† Interestingly, the specific frequency of metal-rich GCs is known to correlate with galaxy luminosity among giant ETGs (Peng *et al.* 2008), as does the characteristic truncation mass $\mathcal{M}_c$ of GC mass functions when expressed as modified Schechter (1976) functions (Jordán *et al.* 2007; Johnson *et al.* 2017).

With this in mind, we consider the hypothesis that the He-enhanced populations that are likely responsible for the UV upturn are produced in massive star clusters and subsequently disperse slowly into the field population of galaxies by means of *dissolution of (primarily) metal-rich GCs in the strong tidal field within the inner regions of luminous ETGs*. This hypothesis is explored below.

We make the assumption that the UV and optical properties of the metal-rich GCs seen in the inner regions of M87, the central ETG of the Virgo galaxy cluster, are representative for massive metal-rich GCs in all ETGs. Specifically, we use the average *m(1550)* and V-band photometry of the metal-rich GCs in the sample of Sohn *et al.* (2006; see also Peacock *et al.* 2017) detected in the far-UV, and we evaluate the range of the number of such GCs within $R_{\rm eff}/2$ of the ETG that can produce the observed range of *m(1550)* − V among ETGs (which is ∼1.5 mag). We find that such UV-bright GCs are predicted to produce V-band luminosity fractions up to $f_V \sim 0.23$ (in the UV-brightest ETGs; see Goudfrooij 2018 for details). To convert f_V to a mass fraction $f_{\rm GC}$, we consider that the central regions of giant ETGs typically feature stellar mass functions similar to a Salpeter IMF or even more bottom heavy (e.g., van Dokkum *et al.* 2017), while massive GCs feature MFs similar to a Kroupa IMF (e.g., Goudfrooij & Fall 2016). The $\mathcal{M}/L_V$ for a Kroupa IMF is a factor 1.75 lower than for a Salpeter IMF at an age of 12 Gyr and [Z/H] = 0, resulting in $f_{\rm GC} \lesssim 0.13$ for the massive UV-bright GCs.

To check whether this range of $f_{\rm GC}$ is consistent with that expected from GC dissolution over a time span similar to the age of giant ETGs (assumed to be 12 Gyr), we use the semi-analytical dynamical evolution model of Goudfrooij & Fall (2016). As is common in dynamical evolution models, we adopt a Schechter (1976) initial cluster mass function (ICMF) in conjunction with evaporation by two-body relaxation in the tidal field of the parent ETG, which is estimated to result in evaporation rates $\mu_{\rm ev}$ in the range $4.0 \leqslant \log\,(\mu_{\rm ev}/(M_\odot\ {\rm Gyr}^{-1})) \leqslant 5.5$ (see Goudfrooij 2018 for the extensive details on this). For the low-mass truncation of the power-law tail of the ICMF, we consider $\mathcal{M}_{0,\rm min}/M_\odot = 10^2$ and 10^3 to allow for an appropriate range of gas pressure during the formation era (Goudfrooij 2018; Trujillo-Gomez *et al.* 2019). For the Schechter truncation mass $\mathcal{M}_c$ we consider values between 10^6 and $10^{7.5}\ M_\odot$, corresponding to the range covered by the luminosities of ETGs in the sample of Goudfrooij (2018; see Johnson *et al.* 2017). To illustrate the results, we evaluate the mass fraction of stars from GCs whose initial mass was above $\mathcal{M}_{\rm limit}$, $f_{\rm GC} = f(\mathcal{M}_{\rm limit},\ \mathcal{M}_c,\ \mu_{\rm ev})$. Figure 2 plots $\Delta f_{\rm GC}$ versus $\mathcal{M}_{\rm limit}$, where $\Delta f_{\rm GC} \equiv f_{\rm GC}\,(\mathcal{M}_{\rm limit}, \mathcal{M}_c, \mu_{\rm ev}) - f_{\rm GC}\,(\mathcal{M}_{\rm limit}, 10^6\ M_\odot, 10^4\ M_\odot\ {\rm Gyr}^{-1})$, i.e., the value of $f_{\rm GC}$ relative to that for $\mathcal{M}_c = 10^6\ M_\odot$ and $\mu_{\rm ev} = 10^4\ M_\odot\ {\rm Gyr}^{-1}$, corresponding to ETGs with the weakest UV upturns.

Note that the range of $\Delta f_{\rm GC}$ implied by the hypothesis that the range of *m(1550)*−V seen among ETGs is produced by (now largely dissolved) massive metal-rich GCs in the inner regions can indeed be reproduced by dynamical evolution of such GCs under very reasonable conditions. Specifically, we find that the range $\Delta f_{\rm GC} \lesssim 0.23$ mentioned above is covered if $\mathcal{M}_c \lesssim 10^7\ M_\odot$, which is entirely consistent with the values for $\mathcal{M}_c$ found for the ETGs with the strongest UV upturns (Johnson *et al.* 2017; Goudfrooij 2018).

In summary, we find that the range of observed *m(1550)*−V colors in the inner regions of nearby ETGs is consistent with our hypothesis that it is produced by He-rich EHB

† Note that galaxies with luminosity-weighted ages < 8 Gyr in the sample of Goudfrooij (2018) were excluded in Figure 1, as was M89 which has an active galactic nucleus.

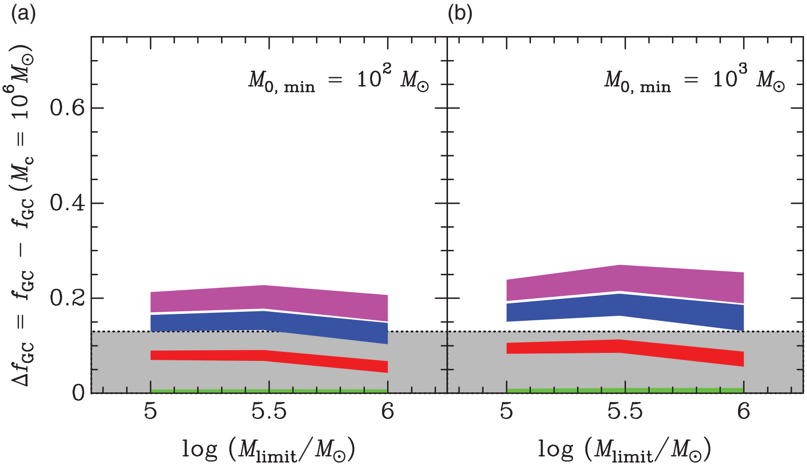

Figure 2. $\Delta f_{\rm GC}$ versus $\mathcal{M}_{\rm limit}$. The colored regions in each panel show results for GC evaporation rates $\mu_{\rm ev}$ in the range $4.0 \leqslant \log(\mu_{\rm ev}/(M_\odot\,{\rm Gyr}^{-1})) \leqslant 5.5$ and different values of $\mathcal{M}_{\rm c}$: $\log(\mathcal{M}_{\rm c}/M_\odot) = 6.0$ (green), $\log(\mathcal{M}_{\rm c}/M_\odot) = 6.5$ (red), $\log(\mathcal{M}_{\rm c}/M_\odot) = 7.0$ (blue), and $\log(\mathcal{M}_{\rm c}/M_\odot) = 7.5$ (magenta). The two panels indicate different assumptions for the low-mass truncation of the ICMF, mentioned at the top right of each panel. The gray region depicts the range of $f_{\rm GC}$ implied by the hypothesis that the range of *m(1550)−V* seen among ETGs is caused by dissolution of massive metal-rich GCs in the inner regions, based on the UV luminosities of massive GCs in M87 observed by Sohn *et al.* (2006). Adapted from Goudfrooij (2018).

stars associated with massive ($\log(\mathcal{M}_0/M_\odot) \gtrsim 5.5$) metal-rich GCs, most of which have dissolved after ∼12 Gyr of dynamical evolution. The *m(1550)−V* colors of ETGs with the weakest UV upturns and low values of S_N are consistent with GCs that were formed in environments featuring relatively low star formation rates, associated with relatively low characteristic truncation masses ($\mathcal{M}_{\rm c} \approx 10^6\ M_\odot$), whereas the GCs in ETGs with the strongest UV upturns and high S_N values were likely formed in vigorously star-forming environments where $\mathcal{M}_{\rm c} \approx 10^7\ M_\odot$. This result is supported by the recent numerical simulations of GC formation at high redshift by Li *et al.* (2017), who found a correlation between $\mathcal{M}_{\rm c}$ and star formation rates (SFR) such that $\mathcal{M}_{\rm c} \propto {\rm SFR}^{1.6}$.

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