The Little Engines That Could? Globular Clusters Contribute Significantly to Reionization-era Star Formation

Michael Boylan-Kolchin

Department of Astronomy, The University of Texas at Austin, 2515 Speedway, Stop C1400, Austin, TX 78712-1205, USA; mbk@astro.as.utexas.edu

ABSTRACT

Metal-poor globular clusters (GCs) are both numerous and ancient, which indicates that they may be important contributors to ionizing radiation in the reionization era. Starting from the observed number density and stellar mass function of old GCs at \( z \approx 0 \), I compute the contribution of GCs to ultraviolet luminosity functions (UVLFs) in the high-redshift Universe (10 \( \lesssim \) \( z \) \( \lesssim \) 4). Even under absolutely minimal assumptions — no disruption of GCs and no reduction in GC stellar mass from early times to the present — GC star formation contributes non-negligibly to the UVLF at luminosities that are accessible to the Hubble Space Telescope (HST; \( M_{1500} \approx -17 \)). If the stellar masses of GCs were significantly higher in the past, as is predicted by most models explaining GC chemical anomalies, then GCs dominate the UV emission from many galaxies in existing deep-field observations. On the other hand, it is difficult to reconcile observed UVLFs with models requiring stellar masses at birth that exceed present-day stellar masses by more than a factor of 5. The James Webb Space Telescope (JWST) will be able to directly detect individual GCs at \( z \approx 6 \) in essentially all bright galaxies, and many galaxies below the knee of the UVLF, for most of the scenarios considered here. The properties of a subset of high-redshift sources with \( -19 \lesssim M_{1500} \lesssim -14 \) in HST lensing fields indicate that they may actually be GCs in formation.

Keywords: globular clusters: general – dark ages, reionization, first stars – galaxies: formation

1 INTRODUCTION

The physics of galaxy formation at high redshift persists as one of the most important questions in astrophysics. While many models exist of the “first galaxies” at \( z \approx 20 \) and putative sources of cosmic reionization at \( z \sim 8 \) (e.g., Bromm & Yoshida 2011; Madau 2017), observational constraints are much more challenging, especially for the lowest luminosity sources. This is a main motivation for JWST, yet even JWST will not reveal the faintest star-forming galaxies in the high-redshift Universe: the stellar fossil record of dwarf galaxies in the Local Group demonstrates the existence of galaxies in the reionization era that are at least 40,000 times fainter than JWST’s detection threshold in blank fields (Boylan-Kolchin et al. 2015; Weisz & Boylan-Kolchin 2017). The integrated ultraviolet (UV) photon output from faint but numerous galaxies is likely crucial for maintaining an ionized intergalactic medium at \( z \sim 6 \) – 8, as bright galaxies simply do not produce enough UV emission to maintain reionization based on our current understanding of their escape fractions (\( f_{esc} \), Kuhlen & Faucher-Giguère 2012; Robertson et al. 2013; Bouwens 2016; Finkelstein 2016; Stark 2016).

While the use of the stellar fossil record for contextualizing dwarf galaxies in the reionization era is a relatively recent phenomenon, the basic idea of using the fossil record to learn about the early Galaxy and its evolution has a long and storied history (Eggen et al. 1962; Peebles & Dicke 1968; Searle & Zinn 1978; Larson 1990; Bland-Hawthorn & Freeman 2000). Globular clusters, in particular, have captured the attention of observers and theorists alike as they try to unravel the mysteries of the early stages of galaxy formation. The Milky Way is surrounded by over 100 old GCs (Harris 1996), and their high stellar densities, characteristic luminosity, and old ages have been the source of intrigue and speculation for decades (for reviews, see Harris 1991; VandenBerg et al. 1996; Brodie & Strader 2006; Charbonnel 2016).

The typical Milky Way GC has a present-day stellar mass of \( 2 \times 10^5 M_\odot \) and an age of 12 – 13 Gyr, placing its formation epoch at or near the reionization era. The sheer number density of GCs (\( n_{GC} \), coupled with their roughly coeval formation times, points to their potential importance for cosmic reionization: using \( n_{GC}(z = 0) = 2 \text{ Mpc}^{-3} \) (Boylan-Kolchin 2017, hereafter B17; see also Portegies Zwart & McMillan 2000) and assuming all GCs formed at high redshifts over a period of \( \Delta t \), the star formation rate from GC stars is \( \rho_{*,GC} = 5 \times 10^{-5} \xi (\Delta t/1000 \text{ Myr})^{-1} M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3} \), where \( \xi \) is the ratio of \( M_* \) at birth to present day. This star formation rate is a non-negligible fraction of what is needed to maintain an ionized intergalactic medium at \( z = 6 \), \( \rho_{*, crit} = 0.012 M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3} \) (Shull et al. 2012, assuming a clumping factor of 3 and an escape fraction of 0.2). Specifically, if the mass in stars formed in GCs is a factor of \( \gtrsim 10 \) larger than their present-day stellar mass, GCs can contribute \( \gtrsim 50\% \) of the requisite ionizing flux (Ricotti 2002; Schaerer & Charbonnel 2011; Katz & Ricotti 2014). Carlberg (2002) made the
related point that the sky density of GCs is likely to be enormous: he estimated $10^7$ deg$^{-2}$ at 1 nJy ($m_{ab} = 31.4$, corresponding to $M_{1500} \approx -15.6$ at $z = 7$).

In this paper, I consider the luminosity function (LF) of GCs in the reionization era from a theoretical perspective, confront these models with observed UVLFs, and comment on the resulting implications for GC formation models, the contribution of GCs to reionization, and the observability of high-redshift GCs with HST and JWST.

2 GLOBULAR CLUSTERS AT HIGH REDSHIFT

In the low-redshift Universe, GC systems around galaxies have a nearly-universal stellar mass function that is log-normal, with characteristic stellar mass of $\sim 2 \times 10^5 M_\odot$ and $\log_{10}$ dispersion of $\sim 0.5 \sim 0.6$ (Harris 1991; Villegas et al. 2010). Taking the known value of $n_{GC}$ in the local Universe, it is possible to compute the GC UVLF at high redshifts by considering only the present-day stellar mass contained in GCs and a specified formation epoch through the use of stellar population synthesis models. One can also vary these assumptions, as several physical effects should affect GC populations through cosmic time:

- **GC $M_*$ at birth relative to present-day $M_*$ ($\xi$):** $\xi = 1$ is an absolute minimum assumption, and most models that explain the multiple stellar populations observed in GCs (see, e.g., Gratton et al. 2012 and Renzini et al. 2015 for recent reviews) require much larger values, $\xi \sim 10 \sim 100$ (e.g., Decressin et al. 2007; D’Ercoloe et al. 2008; Conroy & Spergel 2011; Denissenkov & Hartwick 2014; see Bastian & Lardo 2015 for a critical review of various mass-loss scenarios). Irrespective of the origin of multiple populations, evaporative losses from GCs due to collisional relaxation and mass loss from stellar evolution reduce the stellar mass of a GC over time (Spitzer 1987; Fall & Zhang 2001). Furthermore, GCs are subject to impulsive tidal shocks, as they orbit through the center of a galaxy if the time for the GC to traverse the disk or spheroid is short compared to the orbital period of GC stars. Such shocks irreversibly heat GC stars and can cause additional mass loss (Ostriker et al. 1972; Spitzer 1987; Murali & Weinberg 1997; Gnedin et al. 1999).

The generic expectation from all models of GC evolution, therefore, is that $\xi > 1$ for old GCs.

- **Fraction of GCs surviving to $z = 0$ ($f_{surv}$):** The processes mentioned above are enough to completely disrupt some GCs. In particular, two-body relaxation will tend to disrupt all but the most extended low-mass ($M_* \lesssim 10^5 M_\odot$) GCs over a Hubble time, and tidal shocking should destroy some of the clusters that orbit closest to a galaxy’s center (Chandrasekhar 1942; Spitzer 1987; Fall & Rees 1977; Binney & Tremaine 1987; see Prieto & Gnedin 2008 for estimates of the relative contributions of collisional, stellar evolution, and disruption).

- **Duration of GC formation epoch ($\Delta t$):** While the absolute ages of blue GCs are relatively uncertain, it is clear that (1) blue GCs are ancient, with formation times comparable to the age of the Universe, and (2) the relative age uncertainties are significantly smaller, with a dispersion of approximately 0.4-0.5 Gyr (e.g., Marin-Franch et al. 2009; VandenBerg et al. 2013). I therefore adopt $\Delta t = 1000$ Myr as my default assumption; I also consider the implications of other values of $\Delta t$. 1000 Myr is approximately the time between redshifts 10 and 4 (lookback times between 13.3 and 12.3 Gyr) in the standard cosmological model (Planck Collaboration et al. 2016).

I will assume that the formation rate of globular clusters is a power law function of time, $\dot{n}_{GC} \propto t^{-(1+n)}$, with $n = -1$ (a formation rate that is constant with time) as my fiducial model. Note that under this assumption, $\dot{n}_{GC} = n_{GC}/\Delta t$.

Considering only stars still present at $z = 0$ GCs will result in a lower limit on the contribution of GCs to high-$z$ UVLFs. The effect of $\Delta t$ is a uniform shift of the entire initial GC stellar mass function to higher $M_*$ values (and therefore, to larger values of $L_{1500} \propto \Delta t$), while $f_{surv}$ and $\Delta t$ serve to change the overall normalization of the GC UVLF at early times: $t \rightarrow \phi (f_{surv} \Delta t/1 \text{ Gyr})^{-1}$.

Additionally, it is not clear whether the observed log-normal LF of old GCs at $z = 0$ is reflective of their stellar mass distribution at birth versus a result of dynamical processes operating to preferentially destroy low-mass clusters. In the former case, the log-normal shape could be a manifestation of the Jeans mass in the low-metallicity, high-$z$ Universe (Peebles & Dicke 1968; Fall & Rees 1985) or the result of preferential disruption of low-mass proto-GC gas clouds via supernova feedback (Parmentier & Gilmore 2007; Baumgardt et al. 2008). In the latter case, the mass spectrum of GCs at formation in the high-$z$ Universe would resemble the spectrum of both giant molecular clouds (Solomon et al. 1987; Rosolowsky 2005; Krumholz 2015) and young star clusters forming in low-redshift systems (especially in ongoing or recent galaxy mergers; Whitmore & Schweizer 1995; Larsen 2002; Portegies Zwart et al. 2010); the subsequent evolution to the observed log-normal shape is expected based on the sub-Hubble-time two-body-relaxation timescales for low-mass clusters (Fall & Zhang 2001; Prieto & Gnedin 2008). I will take the initial GC stellar mass function to be log-normal as my default assumption, as using a Schechter-like luminosity function will only result in more GCs and more UV emission at faint magnitudes. However, I explicitly consider the case of a Schechter-like initial stellar mass function and compare to the log-normal case in Appendix B.

2.1 Intrinsic Luminosity Functions

Assuming a log-normal form for the $z = 0$ GC stellar mass function, the UVLF of a cosmologically representative GC system (measured at 1500 Å in the rest frame, $M_{1500}$) may be thought of a log-normal distribution with a mean value $\bar{M}$ that evolves with time. $\bar{M}(t)$ is fully determined by the time evolution of UV emission from a specified stellar population and the time dependence of any mass loss; based on stellar population synthesis calculations outlined in B17, I adopt

$$\bar{M}(t) = -14.5 - 2.5 \log_{10} \left[ \frac{\xi}{t/10^7} \right]^{-b}, \text{ with }$$

$$(a, b) =$$

$$(1, 0) \text{ if } t < 5.5 \text{ Myr}$$

$$\left(9.17, 1.3\right) \text{ if } 5.5 \leq t/\text{Myr} \leq 300$$

$$\left(103, 1.725\right) \text{ if } 300 \leq t/\text{Myr} \leq 1400$$

Fig. 1 shows the evolution of the GC UVLF over the full epoch of GC formation (see Appendix A for details of this calculation). Initially, the GC UVLF traces the log-normal form of the underlying GC mass function. As time progresses, however, two competing effects take place: the earliest-forming GCs fade passively, shifting uniformly to fainter magnitudes, and newly-forming GCs emerge, populating the initial log-normal GC UVLF curve. The full GC UVLF is a sum over populations of GCs of different ages (and, correspondingly, different mean $M_{1500}$ values). The shape of the full GC UVLF is therefore determined by how quickly $M_{1500}$ fades with time for a given GC; for sufficiently fast fading, only the very early stages of GC formation will be important for the UVLF, while

MNRAS 000, 1–9 (2017)
Globular clusters and high-\(z\) luminosity functions

Figure 1. Intrinsic luminosity functions of GCs (uncorrected for any internal extinction). GCs are assumed to have \(\xi = 1\) and to form at a constant rate in time with a formation epoch duration of 1000 Myr. Left: GC UVLFs at 5.5, 50, 100, 250, 500, and 1000 Myr after the start of the GC formation era. While GCs sample a log-normal luminosity function, the combination of passive fading plus continuous GC formation results in a total GC UVLF that develops a power-law tail with a cut-off at faint magnitudes. Right: The contribution of GCs with various ages to the GC UVLF at 1000 Myr. While the youngest GCs (with ages < 5.5 Myr) are the brightest, the GC UVLF is dominated by GCs formed in the previous 5.5–300 Myr.

Figure 2. Luminosity function from GCs in the fiducial model (in which the GC stellar mass function at birth is log-normal) at \(t = 1000\) Myr (solid gray), along with Schechter function approximation (dashed black). The parameters of the Schechter function \((M^*, \alpha, \phi^*)\) are determined by \(\xi, \Delta t\), and stellar evolution (via \(a, b\); see Eq. (1)).

2.2 Contributions of GCs to \(\phi_{UV}\)

Figure 3 compares the intrinsic (unobscured) GC UVLF to measured global UVLFs from \(z = 10\) to \(z = 4\) (as compiled in §5.2-5.3 of Finkelstein 2016). For magnitudes fainter than \(M_{1500} \approx -17\), there is significant uncertainty in the faint-end slope of the UVLF, particularly at \(z \geq 8\). The plotted results assume steeper faint-end slopes compared to some estimates and therefore can be interpreted as providing upper limits to the luminosity function of faint galaxies at early times. For the default assumptions adopted here – \(\xi = 1\), \(\Delta t = 1\) Gyr, and \(f_{surv} = 1\) – GCs contribute a maximum of \(\approx 25\%\) of the UVLF (at \(M_{1500} \approx -15\)), with a lesser contribution for very bright magnitudes (because GCs have a maximum initial stellar mass) and very faint magnitudes (because the observed high-\(z\) UVLFs have very steep faint-end slopes) at most redshifts.

The inferred contribution of GCs to the global UVLF changes dramatically if we consider alternate scenarios, however: the birth masses of GCs (\(\xi\)), GC disruption (\(f_{surv}\)), and the duration of the GC formation epoch (\(\Delta t\)) all have significant effects on the contribution...
of GCs to the global UVLF. The horizontal location of the GC UVLF depends on $\xi$ while its normalization is proportional to $(\xi A_{1500})^{-1}$. These effects are noted with arrows in Fig. 3 and indicate that $\xi = 100$ is extremely difficult to reconcile with observed luminosity functions.

Having established the unobscured GC UVLF, the obvious next question is: do GCs contribute significantly to the global UVLF at high redshifts? To address this question, I need to convert from intrinsic to observed UV fluxes, i.e., to account only for UV (rest-frame 1500 Å) radiation that escapes the GC. A related quantity – the fraction of ionizing radiation that escapes the galaxy, $f_{\text{esc}}$ – is perhaps the most fraught aspect of reionization modeling. Many global models of reionization assume a constant escape fraction of $f_{\text{esc}} \approx 0.1$–0.2 (e.g., Robertson et al. 2013; Finkelstein et al. 2015; Ishigaki et al. 2017). No such consensus exists in simulations, with results ranging from fairly high to virtually negligible values of $f_{\text{esc}}$ (e.g., Wise et al. 2014; Paardekooper et al. 2015; Ma et al. 2015; Xu et al. 2016; Gnedin 2016; Anderson et al. 2017; Howard et al. 2017; Trebitsch et al. 2017; Kimm et al. 2017; Zackrisson et al. 2017). However, the escape fraction of UV radiation (hereafter, $f_{1500}$) will certainly be higher than $f_{\text{esc}}$, the escape fraction of hydrogen-ionizing radiation.

Observations of young massive clusters reveal that they are gas-free within ~5–10 Myr of their birth (Bastian et al. 2014; Holliday et al. 2015), indicating that a combination of stellar winds, radiation pressure, and type II supernovae is highly efficient at completely removing gas from nascent GCs. It is therefore likely that $f_{\text{esc}}$ for GCs depends time relative to $t_{\text{gas-free}}$, where $t_{\text{gas-free}} = 10$ Myr is the assumed timescale for the evacuation of gas from a newly-formed GC; this value is a conservative upper limit. Furthermore, the distribution of GCs within their host halos is significantly more extended than the size of the central galaxy (Hudson & Robison 2017; Forbes 2017), indicating that GCs typically form in regions

that, while locally very dense, are globally embedded in a relatively tenuous medium from which photons can easily escape.

I will therefore consider two possibilities: $f_{1500} = 1$ at all times, or $f_{1500}(t < t_{\text{gas-free}}) = 0$ and $f_{1500}(t > t_{\text{gas-free}}) = 1$ (corresponding to no 1500 Å UV escape prior to gas evacuation and full escape afterward). Lower values of $f_{1500}$ can be modeled by shifting $M_{1500} \rightarrow M_{1500} - 2.5 \log_{10}(f_{1500})$. I consider both $\xi = 1$ and 10 for each $f_{1500}$ scenario. While the $f_{1500} = 0$ scenario is unrealistic, it provides a firm lower limit and therefore serves a useful role in demonstrating the lowest possible contribution of GCs to UVLFs.

Figure 4 compares the GC UVLFs computed using these parameters to the same galaxy UVLFs from Fig. 3. Black curves assume $\xi = 10$ and gray curves assume $\xi = 1$; solid and dashed lines correspond to $f_{1500}(t < t_{\text{gas-free}}) = 1$ and 0, respectively. The models with $\xi = 1$ fall below observations, while both models with $\xi = 10$ exceed observed UVLFs at magnitudes accessible to $HST$ in blank fields ($M_{1500} \lesssim -17$; McLure et al. 2013; Schenker et al. 2013). However, I continue to consider these models with $\xi = 10$ for a number of reasons. First, $f_{1500}$ and $\xi$ can be combined into a single parameter, $\xi \equiv f_{1500}$, this is the quantity that is constrained by observations and the gray (black) lines in Fig 4 are best thought of as lines with $\xi \approx 1$ (10). Second, $\xi \gtrsim 10$ is routinely invoked as a necessity in literature models of light element anti-correlations in GCs. Finally, high values of $\xi$ provide a firm upper limit to the number of GCs that should be detectable in the high-redshift Universe. In both cases ($\xi = 1$ and 10), the faint-end slope of the GC UVLF is very similar to the $z = 4$ UVLF ($\alpha \approx -1.7$). A clear prediction, independent of $\xi$, is that the GC UVLF should extend to high number densities at faint magnitudes; the LF turn-over occurs at $M_{1500} \approx -7.75$ (~10.25) at the end of the GC formation epoch for $\xi = 10$.

Figure 5 compares the GC UVLFs to global UVLFs in ratio

---

**Figure 3.** The intrinsic luminosity function of globular clusters (gray-scale, with line colors identical to those in the left panel of Fig. 1) during their epoch of formation. The plot assumes birth masses are equal to present-day masses ($\xi = 1$) and formation uniformly distributed in time over a period of $\Delta t = 1$ Gyr, approximately the time from $z = 10$ to $z = 4$. Also plotted are observed UV LFs (colored lines) from $z = 10$ (dark purple) to $z = 4$ (light orange) as compiled in Finkelstein (2016). Horizontal arrows indicate the effects of assuming $\xi = 10$ (dark gray) or 100 (black), while the vertical arrow shows the shift in the globular cluster luminosity function if the formation period is 250 Myr. This would also be the shift required if $E_{\text{esc}} = 0.25$ as opposed to 1.
form in order to assess the contribution of GCs to UVLFs explicitly. Dashed lines correspond to $\xi_{\text{eff}} = 10$ and solid lines correspond to $\xi_{\text{eff}} = 1$; in each case, I assume $f_{1500}(t < t_{\text{gas-free}}) = 0$ and 1 at later times. For large values of $\xi_{\text{eff}}$, a large fraction of the global UVLF comes from GCs (in fact, the GC UVLF exceeds the total UVLF at observable magnitudes for $\xi_{\text{eff}} = 10$). The contribution of GCs is substantially lower for $\xi_{\text{eff}} = 1$, particularly for magnitudes brighter than HST’s blank-field limit of $M_{1500} \approx -17$. At fainter magnitudes ($M_{1500} \gtrsim -15$), the contribution of GCs to the UVLF approaches or exceeds 10% at all redshifts. If the faint-end slope of the galaxy UVLF is shallower than the estimates of Finkelstein (2016), the relative contribution of globular clusters would be enhanced relative to what is plotted.

It therefore appears unavoidable that GCs contribute appreciably (at minimum) or perhaps dominantly (for high values of $\xi_{\text{eff}}$) to high-redshift UVLFs. Katz & Ricotti (2013) reached similar conclusions with a complementary approach to computing high-$z$ contributions of GCs to UVLFs. Their derived GC UVLFs are significantly steeper than those obtained here, however: even though their assumed low-mass slope of the initial GC stellar mass function is $-1.5$, Katz & Ricotti (2013) find GC UVLFs that have faint-end slopes that are steeper than $-2$. As is shown in Appendix B, the GC UVLFs calculated here have slopes that are shallower than $-2$ even if the initial GC stellar mass function is assumed to have a slope of $-1.9$.

3 DISCUSSION

The results of the previous section indicate that GCs can contribute substantially to high-redshift UV emission. A natural question, therefore, is whether individual GCs will be detectable by future (or even current) facilities, or if only the sum of the light from multiple GCs will be visible.

Figure 6 shows the probability distribution of $M_{1500}$ from the integrated light in GCs for systems with 1, 10, 100, and 1000 GCs at $z = 6$. The plotted distributions assume $\xi_{\text{eff}} = 1$ and $f_{1500}(t < t_{\text{gas-free}}) = 0$; results for other values of $\xi_{\text{eff}}$ can be obtained through a straightforward rescaling (as noted on the x-axis of the figure). Changing from $f_{1500}(t < t_{\text{gas-free}}) = 0$ to 1 would result in a brightward shift of 0.6 magnitudes for each distribution, as $\approx 40\%$ of the lifetime UV emission of each GC comes in the first 10 Myr based on the assumptions adopted here. If $t_{\text{gas-free}}$ is set to 5 Myr rather than 10 Myr, then 25% of the lifetime UV emission is obscured, corresponding to a brightward shift of 0.3 mag.

Whether or not any individual GC is detectable depends on how likely it is to exceed the detection threshold of a given instrument. Table 1 lists the probability that at least one GC can be directly detected in halos of various masses at $z \approx 6$ with HST or JWST. The $M_{\text{halo}} \sim M_{1500}$ relationship is computed via abundance matching the halo mass function (computed following Sheth et al. 2001 using the Planck Collaboration et al. 2016 cosmology) and the observed $z \sim 6$ UVLF. Results are listed separately for models with $\xi_{\text{eff}} = 1$ (models 1a and 1b) and $\xi_{\text{eff}} = 10$ (models 2a and 2b). For the rarest, most massive halos at $z = 6$ ($M_{\text{halo}} \approx 10^{12} M_{\odot}$, corresponding to $M_{1500} \approx -21.6$), HST will be able to detect at least 1 GC 2-20% of the time if $\xi_{\text{eff}} = 1$ and in virtually every case if $\xi_{\text{eff}} = 10$. JWST can detect at least one GC directly in essentially all scenarios considered here. Moving to lower-mass halos, detection becomes increasingly unlikely. Nevertheless, JWST will detect one GC in 1.5% (39%) of halos with $M_{\text{halo}}(z \sim 6) \approx 10^{10} M_{\odot}$ (corresponding to $M_{1500} \approx -15.6$, which is near the faint limit of JWST detections in hypothetical deep fields) under pessimistic (optimistic) assumptions.

The possibility of detecting GCs, or that some current observations may already be revealing proto-GCs, in the high-redshift Universe was anticipated by Carlberg (2002) and has recently gained significant attention (Schaerer & Charbonnel 2011; Katz & Ricotti 2013).
2013; Bouwens et al. 2017; Boylan-Kolchin 2017; Renzini 2017; Vanzella et al. 2017). In particular, the very small sizes (10s of pc) of intrinsically faint, gravitationally lensed sources at $z \sim 6$ in the Hubble Frontier Fields appear consistent with GCs or star cluster complexes in formation (Kawamata et al. 2015; Vanzella et al. 2017; Bouwens et al. 2017; Kawamata et al. 2018): figure 12 of Bouwens et al. (2017) shows a population of galaxies with roughly constant sizes of $5-15$ pc over the luminosity range $-19.5 \lesssim M_{1500} \lesssim -14$. GCs themselves are likely easier to detect than other objects with similar values of $M_{1500}$, as their surface brightnesses are substantially higher (see Zick et al. 2018 for a more detailed discussion).

Compact, UV-bright sources are also found in simulations of reionization-era galaxies (Kimm et al. 2016; Ma et al. 2017; Kim et al. 2018). The long-term stability of UV clumps is unclear: some may be clusters that are not gravitationally bound and disrupt rapidly after formation (within $\sim 10^7$ years), similar to star clusters in low-redshift merging systems (Bastian et al. 2005; Fall et al. 2005). If this is the case, an even higher fraction of high-redshift star formation may occur in dense, GC-like systems than the estimates in this paper imply, as these disrupting clusters would not evolve into GCs at $z = 0$. In fact, it may be possible to model high-$z$ UVLFs using the tools presented here in the limit that all stars form in clusters with either log-normal or Schechter-like shapes.

There is certainly room for improvement in the modeling presented here. Perhaps the most important refinement would be to include a $M_\star$ dependence in $\xi_{\text{eff}}$; detailed estimates of $f_{\text{star}}$ would also be highly informative. A better understanding of both absolute and relative ages for blue GCs is also essential to model their relevance in the reionization era and to constrain $\Delta t$ (though it appears difficult to reconcile a later formation epoch with observed properties of $z \sim 4$ galaxies; Katz & Ricotti 2013). The stellar IMF is also a source of uncertainty: more top-heavy IMFs will produce more UV luminosity per unit stellar mass, changing the relationship between $M_{1500}$ and $M_\star$. Nonetheless, the power of the relatively straightforward models described in this paper to directly constrain properties of GCs in the high-redshift Universe and their contributions to cosmic reionization is encouraging. Some “galaxies” already detected in HST deep fields are likely to be GCs in formation; in the JWST era, observations of GCs in formation should be commonplace.

ACKNOWLEDGMENTS

I thank Charlie Conroy and Dan Weisz for insightful comments on earlier versions of this paper; Michael Fall, Kristian Finlator, Oleg Gnedin, Pawan Kumar, Smadar Naoz, Eliot Quataert, Charli Sakari, Chris Sneden, and Eros Vanzella for helpful discussions; and Tom Petty for aural support. Support for this work was provided by The University of Texas at Austin, the National Science Foundation (grant AST-1517226), and NASA through grant NNX17AG29G and HST grants AR-12836, AR-13888, AR-13896, GO-14191, and AR-14282 awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Much of the analysis in this paper relied on the python packages NumPy (Van Der Walt et al. 2011), SciPy (Oliphant 2007), Matplotlib (Hunter 2007), and iPython (Pérez & Granger 2007); I am very grateful to the developers of these tools. This research has made extensive use of NASA’s Astrophysics Data System (http://adsabs.harvard.edu) and the arXiv eprint service (http://arxiv.org).

Figure 5. Ratio of GC UVLFs to global UVLFs at a variety of redshifts under the assumption that $\xi = 1$ (solid lines) or 10 (dashed lines), assuming $f_{500} = 0$ for $t < t_{\text{gas-free}}$ and 1 otherwise. If $\xi = 1$, then $\lesssim 1\%$ of the UVLF accessible to HST in blank fields ($M_{1500} < -17$) originates from GCs; by $M_{1500} = -14$, approximately 20% of the UVLF comes from GCs. The GC UVLF actually exceeds the global UVLF at most redshifts at magnitudes accessible to HST if $\xi = 10$.

Figure 6. Probability distributions for $M_{1500}$ from GCs (integrated over a halo’s GC population) for halos of 4 different masses at $z \sim 6$. Halos at the threshold of GC formation ($M_{\text{halo}}(z = 6) = 10^9 M_\odot$, B17) span a wide range of possible values of $M_{1500}$, as any individual GC has a wide range of possible masses and formation times. At increasingly high masses, and correspondingly higher numbers of GCs, the widths of the distributions shrink, as the GCs come closer to fully sampling the underlying luminosity function. All calculations for the plot assume that $\xi_{\text{eff}} = 1$ (though the results can easily be scaled to other values of $\xi_{\text{eff}}$, as is indicated on the x-axis) and $f_{500}(t < t_{\text{gas-free}}) = 0$; the probability distribution for a $10^{12} M_\odot$ halo has been rescaled downward by a factor of 2 to decrease the dynamic range.
Columns 4 and 5 give the fraction of such halos that will host at least one observable GC for HST (assumed detection threshold of $M_{1500} = -17$) and JWST (assumed detection threshold of $M_{1500} = -15$).

### REFERENCES

Abramowicz M., Stegau I.A., 1972, Handbook of Mathematical Functions
Anderson L., Governato F., Karcher M., Quinn T., Wadsley J., 2017, MNRAS, 468, 4077
Bastian N., Lardo C., 2015, MNRAS, 453, 357
Bastian N., Gieles M., Lamers H. J. G. L. M., Scheepmaker R. A., de Grijs R., 2005, A&A, 431, 905
Bastian N., Hollyhead K., Cabrera-Ziri L., 2014, MNRAS, 445, 378
Bass S., Gil M., Audley S., 2015, MNRAS, 449, 2413
B Baumgardt H., Kroupa P., Portegies Zwart S. F., McMillan S. L. W., 2000, ApJ, 528, L17
Charbonnel C., 2016, in Moraux E., Lebreton Y., Charbonnel C., eds, EAS Publications Series Vol. 80, EAS Publications Series, pp 177–226 (arXiv:1611.08855), doi:10.1051/eas/1680006
Conroy C., Spergel D. N., 2011, ApJ, 726, 36
D’Ercole A., Vesperini E., D’Antona F., McMillan S. L. W., Vecchi S., 2008, MNRAS, 391, 825
Decressin T., Meynet G., Charbonnel C., Prantzos N., Ekström S., 2007, A&A, 464, 1029
Denissenkov P. A., Hartwick F. D. A., 2014, MNRAS, 437, L21
Eggber A. O., Lynden-Bell D., Sundage A. R., 1962, ApJ, 136, 748
Fall S. M., Rees M. J., 1977, MNRAS, 181, 37P
Fall S. M., Rees M. J., 1985, ApJ, 298, 18
Fall S. M., Zhang Q., 2001, ApJ, 561, 751
Fall S. M., Chandar R., Whitmore B. C., 2005, ApJ, 631, L133
Finkelstein S. L., 2016, Publ. Astron. Soc. Australia, 33, e037
Finkelstein S. L., et al., 2015, ApJ, 810, 71
Forbes D. A., 2017, MNRAS, 472, L104
Greif N. Y., 2016, ApJ, 823, L17
Gnedin O. Y., Hernquist L., Ostrikov K. P., 1999, ApJ, 514, 109
Gratton R. G., Carretta E., Bragaglia A., 2012, A&A Rev., 20, 50
Harris W. E., 1991, ARA&A, 29, 543
Harris W. E., 1996, AJ, 112, 1487
Hollyhead K., Bastian N., Adamo A., Silva-Villa E., Dale J., Ryon J. E., Gazak Z., 2015, MNRAS, 449, 1106
Howard C. S., Pudritz R. E., Harris B. E., Klessen R. S., 2017, arXiv:1710.04283 [astro-ph]
Hudson M. J., Robison B., 2017, arXiv:1707.02609 [astro-ph]
Hunter J. D., 2007, Computing In Science & Engineering, 9, 90
Ishigaki M., Kawatama R., Ouchi M., Oguri M., Shimasaku K., Ono Y., 2017, arXiv:1702.04867 [astro-ph]
Katz H., Ricotti M., 2013, MNRAS, 432, 3250
Katz H., Ricotti M., 2014, MNRAS, 444, 2377
Kawatama R., Ishigaki M., Shimasaku K., Oguri M., Ouchi M., 2015, ApJ, 804, 103
Kawatama R., Ishigaki M., Shimasaku K., Oguri M., Ouchi M., Tanigawa S., 2018, ApJ, 855, 4
Kim J.-h., et al., 2018, MNRAS, 474, 4232
Kimm T., Cen R., Rosdahl J., Yi S. K., 2016, ApJ, 823, 52
Kimm T., Katz H., Haehnelt M., Rosdahl J., Devriendt J., Slyz A., 2017, MNRAS, 466, 4826
Kroupa P., 2001, MNRAS, 322, 321
Krumholz M. R., 2015, arXiv:1511.03457 [astro-ph]
Kuhlen M., Faucher-Giguère C.-A., 2012, MNRAS, 423, 862
Larsen S. S., 2002, AJ, 124, 1393
Larson R. B., 1990, PASP, 102, 709
Ma X., Kasen D., Hopkins P. F., Faucher-Giguère C.-A., Quataert E., Kereš D., Murray N., 2015, MNRAS, 453, 960
Ma X., et al., 2017, arXiv:1710.00008 [astro-ph]
Madau P., 2017, ApJ, 851, 50
Marin-Franch A., et al., 2009, ApJ, 694, 1498
McLure R. J., et al., 2013, MNRAS, 432, 2696
Murai C., Weinberg M. D., 1997, MNRAS, 291, 717
Oliphant T. E., 2007, Computing in Science Engineering, 9
Ostriker J. P., Spitzer L. J., Chevalier R. A., 1972, ApJ, 176, L51
Paardekooper J.-P., Kchoharf D., Dalla Vecchia C., 2015, MNRAS, 451, 2544
Parmentier G., Gilmore G., 2007, MNRAS, 377, 352
Peebles P. J. E., Dicke R. H., 1968, ApJ, 154, 891
Pérez F., Granger B. E., 2007, Computing in Science and Engineering, 9, 21
Planck Collaboration et al., 2016, A&A, 594, A13
Portegies Zwart S. F., McMillan S. L. W., 2000, ApJ, 528, L17
Portegies Zwart S. F., McMillan S. L. W., Gieles M., 2010, ARA&A, 48, 431
Prieto J. L., Gnedin O. Y., 2008, ApJ, 689, 919
Renzini A., 2017, MNRAS, 469, L63
Renzini A., et al., 2015, MNRAS, 454, 4197
Ricotti M., 2002, MNRAS, 336, L31
Robertson B. E., et al., 2013, ApJ, 768, 71
Rosolowsky E., 2005, PASP, 117, 1403
Schaefer D., Charbonnel C., 2011, MNRAS, 413, 2297
Schechter P., 1976, ApJ, 203, 297
Schenker M. A., et al., 2013, ApJ, 768, 196
Searle L., Zinn R., 1978, ApJ, 225, 357
Sheth R. K., Mo H. J., Tormen G., 2001, MNRAS, 323, 1
Shull J. M., Harness A., Trenti M., Smith B. D., 2012, ApJ, 747, 100
Solomon P. M., Rivolo A. R., Barrett J., Yahil A., 1987, ApJ, 319, 730
Spitzer Jr. L., 1958, ApJ, 127, 17
Spitzer L., 1987, Dynamical Evolution of Globular Clusters. Princeton, NJ, Princeton University Press
Stark D. P., 2016, ARA&A, 54, 761
Trebitsch M., Blaizot J., Rosdahl J., Devriendt J., Slyz A., 2017, MNRAS, 470, 224
Van Der Walt S., Colbert S. C., Varoquaux G., 2011, arXiv:1102.1523 [astro-ph]
VandenBerg D. A., Bolte M., Stetson P. B., 1996, Annual Review of Astronomy and Astrophysics, 34, 461
VandenBerg D. A., Brogaard K., Leaman R., Casagrande L., 2013, ApJ, 775, 134
Vanzella E., et al., 2017, MNRAS, 467, 4304
Villegas D., et al., 2010, ApJ, 717, 603
Weisz D. R., Boylan-Kolchin M., 2017, MNRAS, 469, L83
Whitmore B. C., Schweizer F., 1995, AJ, 109, 960
Wise J. H., demchenko V. G., Halicke M. T., Norman M. L., Turk M. J., Abel T. Smith B. D., 2014, MNRAS, 442, 2560
Xu H., Wise J. H., Norman M. L., Ahn K., O’Shea B. W., 2016, ApJ, 833, 84
Zackrisson E., et al., 2017, ApJ, 836, 78
Zick T. O., Weisz D. R., Boylan-Kolchin M., 2018, arXiv:1802.06801 [astro-ph]

APPENDIX A: LOG-NORMAL LUMINOSITY FUNCTIONS

The component of the GCLF originating from GCs with ages in the range \( [t_i, t] \) can then be written as a time integral over the individual cluster luminosity functions:

\[
\phi(GC)(M, t) \propto \int_{t_i}^{t} \exp \left( \frac{(M - M(t))^2}{\sqrt{2}\sigma^2} \right) f(t) \, dt .
\]  

(A1)

If \( f(t) \propto t^{-(1+\eta)} \), the resulting integral can be computed analytically (Basu et al. 2015):

\[
\phi(GC)(M, t) \propto \exp \left( \frac{\eta B}{C} + \frac{\eta^2}{4C^2} \right) \left[ E_{\eta}(t) - E_{\eta}(t_i) \right],
\]  

(A2)

where

\[
B = \frac{M - M^*}{\sqrt{2}\sigma^2},
\]  

(A4)

\[
C = \frac{2.5b}{\ln(10)\sqrt{2} \sigma^2}, \quad \text{and}
\]  

(A5)

\[
M^* = -14.5 - 2.5 \log_{10}(\xi a) .
\]  

(A6)

I will assume \( \eta = -1 \) (i.e., \( \dot{\eta}_{GC} \) is constant). The full intrinsic GC UVLF is then a sum over component \( \phi(GC)(M, t) \) values, with piecewise time ranges specified by Eq. (2), appropriately normalized for the time evolution of \( \dot{\eta}_{GC} \).

**Figure B1.** A comparison between the derived GC UVLF at the end of the GC formation epoch (after 1 Gyr) under the assumption of initially log-normal or Schechter-like GC stellar mass functions (gray and black, respectively). The GC UVLF in the case of a Schechter-like stellar mass function is itself Schechter-like, with a faint-end slope that is either the same as the underlying Schechter function (\( \alpha \)) or, if the input Schechter function slope is shallower than \(-1.7\), is \(-1.7\) (see discussion below Eq. (B5)).

**APPENDIX B: SCHECHTER LUMINOSITY FUNCTIONS**

The results of this paper generally assume that the observed log-normal luminosity function of GCs is a manifestation of the initial conditions. However, this may not be the case: an initially Schechter-like luminosity function can evolve to a log-normal one over a Hubble time.

The Schechter (1976) luminosity function is parametrized by a normalization \( \phi^* \), a characteristic luminosity \( L^* \), and a faint-end slope \( \alpha \):

\[
\phi(L) = \phi^* \left( \frac{L}{L^*} \right)^\alpha \exp \left( -\frac{L}{L^*} \right)
\]  

(B1)

Analogously to the case of the log-normal luminosity function, we can consider \( L^* \) to be a function of time and compute the GC UVLF as an integral:

\[
\phi(L, t) \propto \int \phi(L, L^*(t)) \frac{dt}{\Delta t}
\]  

(B2)

(where I have assumed \( \dot{\eta}_{GC} \) is constant, consistent with the rest of this paper; it is straightforward to generalize to a power-law dependence on time). With the time evolution of \( L^* \) given by

\[
L^*(t) = L_0 \left( \frac{t}{t_0} \right)^{-b},
\]  

(B3)

the luminosity function becomes

\[
\phi(L) = \phi^* \left( \frac{L}{L_0} \right)^{-1-1/b} \left( \frac{t}{t_0} \right)^{1/b} \left( \frac{L}{L_0} \right)^{\gamma(a, b)},
\]  

(B4)

where

\[
\lambda = a + \frac{1}{b} + 1,
\]  

(B5)

\[
\gamma(a, b) = \left( \frac{a}{\lambda} - b \right) / \lambda .
\]  

(B6)
As with the log-normal case, the GCLF is sum over individual components corresponding to the piecewise time ranges in Eq. (2).

The faint-end slope of $\phi(L)$ in the limit $L \ll L_0$ will be approximately $-1 - 1/b$ if $\alpha > -1 - 1/b$ and $\alpha$ otherwise, as $\gamma(\lambda, u) \propto u^\lambda$ as $u \to 0$. Notably, this faint-end slope is identical to the log-normal case for relatively shallow values of $\alpha$, which is a direct result of the time evolution of $L^*(t) -$ determined by stellar evolution – in Eq. (B3). If the faint-end slope of the initial GC stellar mass function is steeper than $-(1 + 1/b)$, then it is this initial faint-end slope that sets the overall slope of $\phi_{GC}(L)$.

Fig. B1 compares the GC UVLFs (after 1000 Myr of GC formation) for initial GC stellar mass functions that are Schechter-like (with faint-end slope $-1.9$; black line) and log-normal (gray). The input initial GC stellar mass functions are normalized such that the number of GCs brighter than $\tilde{M}$ (the peak value in the log-normal stellar mass function) are equal. The resulting GC UVLFs are nearly identical for bright magnitudes, while the Schechter-like initial GC stellar mass function results in a higher amplitude for $\phi_{GC}(L)$ at fainter magnitudes.