Local Group ultra-faint dwarf galaxies in the reionization era

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ABSTRACT
Motivated by the stellar fossil record of Local Group (LG) dwarf galaxies, we show that the star-forming ancestors of the faintest ultra-faint dwarf galaxies (UFDs; $M_V \sim -2$ or $M_* \sim 10^2$ at $z = 0$) had ultraviolet (UV) luminosities of $M_{UV} \sim -3$ to $-6$ during reionization ($z \sim 6$–10). The existence of such faint galaxies has substantial implications for early epochs of galaxy formation and reionization. If the faint-end slopes of the UV luminosity functions (UVLFs) during reionization are steep ($\alpha \lesssim -2$) to $M_{UV} \sim -3$, then (i) the ancestors of UFDs produced >50 per cent of UV flux from galaxies; (ii) galaxies can maintain reionization with escape fractions that are more than two times lower than currently adopted values; (iii) direct Hubble Space Telescope and James Webb Space Telescope observations may detect only $\sim$10–50 per cent of the UV light from galaxies; and (iv) the cosmic star formation history increases by $\lesssim 4$–6 at $z \gtrsim 6$. Significant flux from UFDs, and resultant tensions with LG dwarf galaxy counts, is reduced if the high-redshift UVLF turns over. Independent of the UVLF shape, the existence of a large population of UFDs requires a non-zero luminosity function to $M_{UV} \sim -3$ during reionization.

Key words: Hertzsprung-Russell and colour-magnitude – galaxies: dwarf–galaxies: high-redshift – Local Group – galaxies: luminosity function, mass function – early Universe.

1 INTRODUCTION

Low-mass galaxy associations to play a central role in ionizing the neutral intergalactic medium (IGM) in the early Universe. While sources such as active galactic nuclei and X-ray binaries may contribute ionizing photons (McQuinn 2012; Madau & Haardt 2015), the consensus view is that a large population of low-mass galaxies is required to explain the observed ionization fraction of the IGM and the Thomson optical depth ($\tau_e$) during reionization (e.g. Finkelstein et al. 2012; Stark 2016).

However, the low-mass galaxy population associated with reionization has never been directly detected. The deepest available blank-field Hubble Space Telescope (HST) observations reach only $M_{UV}(z \sim 7) \sim -17$ (e.g. Bouwens et al. 2015; Finkelstein et al. 2015), but contemporary models of the high-z Universe (e.g. Kuhlen et al. 2012; Robertson et al. 2013, 2015) require the ultraviolet luminosity function (UVLF) to remain steep to magnitudes as faint as $M_{UV}(z \sim 7) = -10$ in order for galaxies to maintain reionization. Gravitational lensing and the exquisite sensitivity of the James Webb Space Telescope (JWST) promise to push observations further down the galaxy UVLF [e.g. to $M_{UV}(z \sim 7) \sim -14$], but the direct detection and characterization of a significant number of intrinsically faint galaxies ($M_{UV} \sim -10$) in the reionization era appears beyond observational capabilities for the foreseeable future. Consequently, the contribution of low-mass galaxies to reionization will continue to be estimated by extrapolating the observed UVLF to galaxies that cannot be directly observed.

Concurrent with searches for faint galaxies at high redshifts, there has been a renaissance in the discovery of extremely faint, low-mass galaxies in the Local Group (LG; e.g. Willman et al. 2005; Belokurov et al. 2006; Zucker et al. 2006; Irwin et al. 2007; Koposov et al. 2007; Bechtol et al. 2015; Kim et al. 2015; Koposov et al. 2015; Laevens et al. 2015; Martin et al. 2015). Deep, wide-field photometric surveys (e.g. Sloan Digital Sky Survey, Dark Energy Survey) have identified dozens of faint galaxies surrounding the Milky Way (MW) with luminosities as low as $M_V \sim -2$ ($M_* \sim 10^3 M_\odot$), and these detections likely represent only a fraction of the low-mass galaxy population in the LG owing to various observational biases (e.g. Koposov et al. 2008; Tolliner et al. 2008; Walsh et al. 2009).

These so-called ‘ultra-faint’ dwarf galaxies (UFDs) host predominantly ancient (>1 Gyr), extremely metal poor ([Fe/H] < -2) stellar populations (e.g. Frebel & Norris 2015). They are thus consistent with being ‘fossils of reionization’ (e.g. Ricotti & Gnedin 2005; Okamoto et al. 2012; Brown et al. 2014; Weisz et al. 2014b): UFDs were star-forming galaxies in the early Universe until UV radiation from reionization stunted their formation (e.g. Bovill & Ricotti 2009).

Though the connection between reionization and truncated star formation in UFDs appears well-established, the possible contribution of the ancestors of UFDs – low-mass star-forming galaxies – to cosmic reionization is far less appreciated. In this
Letter, we address this point by combining the observed stellar fossil record of UFDs around the MW with stellar population synthesis models in order to quantify the role of UFDs in reionizing the early Universe. Specifically, we infer the evolution of the UV luminosities of the lowest mass UFDs across cosmic time and explicitly estimate (i) \( M_{\text{UV}} \), the minimum UV luminosity of star-forming galaxies during the epoch of reionization; and (ii) the effects such systems have on our understanding of the high-redshift (\( z \gtrsim 6 \)) Universe. The focus of this Letter is primarily on demonstrating the existence of extremely faint galaxies at high redshifts, with some exploration of the broader consequences. We will pursue detailed calculations (e.g. computing the reionization history of the Universe including UFDs) in a follow-up Letter. Throughout this Letter, we adopt a Planck Collaboration XIII (2016) cosmology.

2 METHODOLOGY

We combine the star formation histories (SFHs) of UFDs located around the MW measured from the stellar fossil record with the FSPS code (Flexible Stellar Population Synthesis; Conroy et al. 2009, 2010) to compute their integrated UV luminosities as a function of redshift. This methodology is detailed in Weisz et al. (2014c) and Boylan-Kolchin et al. (2015). Here, we summarize the technique and briefly describe assumptions specific to this analysis.

The SFHs of UFDs have been measured by analysing deep HST-based colour–magnitude diagrams (CMDs) for a dozen galaxies located in the immediate vicinity of the MW (e.g. Brown et al. 2014; Weisz et al. 2014a). From measurements, we construct a fiducial SFH of a UFD: 70 per cent of its total stellar mass \( M_\star(z = 0) \approx 5 \times 10^2 M_\odot \) forms in an \( \sim 100 \) Myr interval in the range \( z \approx 9-11 \), and the remaining 30 per cent forms over an \( \sim 2.5 \) Gyr period, which ends at \( z \approx 3 \). This SFH is consistent with observations of LG UFDs (e.g. Brown et al. 2014; Weisz et al. 2014b) and fits well with a scenario in which the UV background suppresses the accretion of fresh gas on to UFDs, allowing for (very) low-level star formation to continue post-reionization (e.g. Ohoro et al. 2015).

This baseline SFH is plotted in the top panel of Fig. 1, and the bottom panel of the figure shows the corresponding integrated UV-band (black) and V-band (orange) flux evolution. We construct these profiles using FSPS, a Kroupa initial mass function (IMF) (Kroupa 2001), the Padova stellar evolution models (Girardi et al. 2010) and a single metallicity of [Fe/H] = −2.0. We assume no dust, which is consistent with the observed spectral energy distributions (SEDs) of the faintest high-redshift galaxies (e.g. Bouwens et al. 2014). Finally, we normalize the computed fluxes to have \( M_\star(z = 0) = -2 \), a value comparable to the faintest known UFDs around the MW (cf. McConnachie 2012).

Our fiducial model is designed to broadly reflect the behaviour of a typical UFD, not encompassing all possible scenarios. To illustrate the effects of another plausible SFH, we consider the case in which 90 per cent of the stellar mass formed in the range \( z \approx 9-11 \). The difference in the UV flux between this alternate SFH and our default model is no more than 0.5 mag (magenta dashed line in Fig. 1). Beyond varying the SFH, other physical effects (e.g. interacting binaries, stochastic sampling of the IMF or various burst permutations of the SFHs; Fumagalli et al. 2011; Weisz et al. 2012; Díaz et al. 2015; Stanway et al. 2016) can affect the UV and ionizing flux output from a galaxy. However, the amplitude of these effects (\( \sim 1-2 \) mag) is not sufficiently large to change our main conclusions.

3 RESULTS AND DISCUSSION

Fig. 1 illustrates the main result of this Letter: The stellar fossil record in the LG demonstrates that star-forming galaxies as faint as \( M_{\text{UV}} = -3 \) existed during the epoch of reionization (\( z \approx 6-10 \)). Over that period, the UV magnitudes of such objects initially decline by \( \sim 3 \) mag, as expected from a constant SFH in the range \( z \approx 9-11 \). This period is followed by a gradual decline in integrated UV and optical flux in the range \( z \approx 3-9 \), when the SFH is constant but lower by a factor of \( \sim 10 \) relative to its peak. Once star formation shuts off at \( z \approx 3 \), the UV flux falls off precipitously owing to the rapid death of UV-luminous young stars. Over the same period, the optical luminosity declines more gradually, as it originates from stars with a wider range of masses. Finally, the upturn in UV luminosity at late times (\( z \lesssim 0.2 \)) stems from the onset of blue horizontal branch stars, which dominate the UV light in the absence of young stars.
of the flux is generated by galaxies brighter than $M_{\text{UV}} = -10$. Faint galaxies make a larger contribution at $z \sim 6–7$, as the faint-end slope is steeper ($\alpha \sim -2$). Galaxies fainter than current HST blank-field limits ($M_{\text{UV}} \sim -17$) contribute 80 per cent of the total UV flux. Thus, the deepest direct observations of the early Universe resolve only 20 per cent of the total UV light from galaxies. Furthermore, galaxies fainter than $M_{\text{UV}} = -10$ contribute 50 per cent of the total UV flux. Future blank-field observations with JWST are projected to extend to $M_{\text{UV}} \sim -14$, which will resolve 40 per cent of the total UV flux from galaxies.

Some observations suggest that the faint-end slope may be as steep as $\sim -2.4$ at $z \sim 8$ (e.g. Finkelstein et al. 2015), increasing the importance of faint galaxies. Although uncertainties remain large ($\sim 0.4$ dex), we consider two UVLFs at $z \sim 8$, with $\alpha = -2.02$ and $-2.36$ (Bouwens et al. 2015; Finkelstein et al. 2015). For the shallower slope, the contribution of faint galaxies is identical to the $z \sim 6–7$ scenario. For the steeper slope, $> 85$ per cent of the instantaneous UV flux comes from galaxies fainter than $M_{\text{UV}} = -10$. In either case, the deepest blank-field HST and future JWST observations are sensitive only to at most 10 per cent of the UV light. This trend may continue at $z \sim 9–10$, where current measurements favour faint-end slopes of $\alpha \sim -2.3$ (e.g. Bouwens et al. 2016), albeit with large uncertainties.

Additional UV and ionizing flux from UFDs implies that galaxies could maintain reionization with smaller escape fractions ($f_{\text{escape}}$) for ionizing photons. For example, Robertson et al. (2013) assume $f_{\text{escape}} = 0.2, \alpha = -2, M_{\text{min}} = -10$ for galaxies to maintain reionization. However, adopting $f_{\text{escape}} = 0.1$ and $M_{\text{min}} = -3.1$ yields the same total ionizing flux. If the faint-end slope is as steep as $\alpha < -2.4$, then $f_{\text{escape}} = 0.02$ and $M_{\text{min}} = -3.1$ would also maintain reionization. Values of $f_{\text{escape}}$ between 2 and 10 per cent appear consistent with several observational and theoretical results (e.g. Leitet et al. 2013; Ma et al. 2015; Siana et al. 2015).

Extra UV flux from UFDs could also imply a higher ionization fraction of the IGM at times earlier than indicated by Planck Collaboration XIII (2016). That is, if UFDs formed early enough and the UVLF was sufficiently steep, then UFDs may have provided enough flux to initiate reionization earlier than $z \sim 10$. While an interesting potential conflict, there are still too many uncertainties that could mitigate this concern. For example, the stellar fossil record of UFDs is not yet capable of differentiating between star formation that started at $z \sim 10$ and that started at $z \sim 12$ (100 Myr in time), which is required to directly compare measurements from UFDs with constraints from Planck. For this Letter, we have adopted $z \sim 11$ for the start of star formation. This is in some tension ($< 2\sigma$) with Planck constraints on $\tau_e$, but only if the UVLF is very steep at $z \gtrsim 10$.

### 3.1 Assuming steep luminosity functions and faint star-forming galaxies

The number density of star-forming galaxies in the early Universe appears well-described by a Schechter function with a faint-end slope that steepens with increasing redshift (e.g. Bouwens et al. 2015; Finkelstein et al. 2015). In this section, we briefly explore the consequences of assuming this functional form of the UVLF remains valid into the regime of UFDs. We consider the alternative – that the high-$z$ UVLF breaks to a shallower slope – in Section 3.2.

#### 3.1.1 Reionization

Scenarios for galaxy-driven reionization typically require integration of the UVLF to a lower luminosity limit of $M_{\text{min}} = -10$ to $-13$ at $z \gtrsim 6$ (e.g. Kuhlen et al. 2012; Robertson et al. 2013, 2015). However, the faint ancestors of UFDs extend $M_{\text{min}}$ fainter by an additional $\sim 7$ mag. The $M_{\text{UV}}(z)$ values for our fiducial UFD more accurately reflect the true lower luminosity limit of star-forming galaxies in the early Universe.

Fig. 2 shows that extending $M_{\text{min}}$ into the regime of UFDs (again, assuming that the faint-end slope of the LF remains unchanged) results in a substantial increase in the amount of total UV (and, by extension, ionizing) flux produced by faint galaxies. The smallest flux contribution from UFDs is at low redshifts ($z \sim 4–5$), where the faint-end slope is fairly flat ($\alpha \sim -1.5$ to $-1.7$); over 90 per cent

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**Figure 2.** Top panel: Schechter UVLFs in the range $z \sim 4–8$ from Finkelstein et al. (2015), along with a $z \sim 8$ UVLF from Bouwens et al. (2015), based on direct measurements of distant galaxies. The UVLFs are plotted to $M_{\text{UV}} \sim -3$, the approximate faint magnitude limit based on the stellar fossil record of UFDs found in the LG. Values of the faint-end slopes range from $\alpha \sim -1.6$ at $z \sim 4$ to $\alpha \sim -2.4$ at $z \sim 8$. Bottom panel: the fraction of UV flux as a function of $M_{\text{UV}}$ for the Schechter UVLFs plotted in the top panel, integrated to values plotted in Fig. 1. For $z \gtrsim 6$, UFDs contribute 50–90 per cent of the total UV flux from galaxies.
Figure 3. The cosmic SFH, with no correction for dust, computed by integrating literature UVLFs at each redshift to different values of $M_{\text{min}}$, and assuming $\alpha = -2.02$ at $z \sim 8$. The solid purple line is the fiducial cosmic SFH from Madau & Dickinson (2014). The magenta line reflects the cosmic SFH when $M_{\text{min}} = -10$, the canonical faint limit for galaxies to maintain reionization (e.g. Robertson et al. 2015), while the orange line includes the contribution of UFDs. The solid points at $z \sim 8$ illustrate the effects of the steeper faint-end slope ($\alpha = -2.36$), as reported in Finkelstein et al. (2015). Including UFDs in the calculation of the cosmic SFH can boost the SFR density of the Universe by factors of $\gtrsim 4$–100 at $z \gtrsim 6$ if the UVLF remains steep.

coloured lines in Fig. 3 show the cosmic SFH integrated to three values of $M_{\text{min}}$: $-17$ (solid purple), $-10$ (solid magenta) and values shown in Fig. 1 for $z \gtrsim 3$ and $-10$ otherwise (solid orange). The coloured points at $z \sim 8$ indicate changes to the cosmic SFH if the steeper faint-end slope of $\alpha = -2.36$ is used (Finkelstein et al. 2015).

Relative to the fiducial assumptions (solid purple), adopting $M_{\text{min}} = -10$ increases the SFR density of the Universe by a factor of $\sim 2$–3 for $z \gtrsim 6$. Adopting values of $M_{\text{min}}$ from the faintest UFDs yields an increase by factors of $\sim 4$–6. At $z \sim 8$, selecting the steeper faint-end slope ($\alpha = -2.36$) results in substantial changes in the cosmic SFH: an increase by a factor of $\sim 15$ for $M_{\text{min}} = -10$ (magenta point) and $\sim 130$ for $M_{\text{min}} = -3.1$ (orange point). Such large increases are also expected at $z \sim 9$–10 if the faint-end slope is steep ($\alpha = -2.3$; e.g. Bouwens et al. 2016). The large (100 times) increase in SFRs implied by the very steep faint-end slopes at $z \gtrsim 6$ may be at odds with the SFR density implied by high-redshift gamma-ray-burst (GRB) observations (e.g. Kistler 2009, 2013; Chary et al. 2016). However, it is presently unclear if GRB measurements are unbiased tracers of star formation in the early Universe (e.g. Madau & Dickinson 2014).

3.1.3 Dark matter halo masses

Establishing the halo masses of faint galaxies in the early Universe is central to our understanding of primordial galaxy formation. Using the stellar–halo mass relation (SMH) as described in Boylan-Kolchin et al. (2014), we estimate that a galaxy with $M_{\text{UV}}(z = 7) = -3.1$ is hosted in a halo with $M_{\text{halo}}(z = 7) \sim 10^9 M_\odot$. This result is insensitive to the SMH.

Taken at face value, this halo mass seems in reasonable agreement with predictions for the first mini-haloes (e.g. Wise et al. 2012). However, it is also well below the virial mass ($\sim 10^8 M_\odot$) that corresponds to the atomic cooling limit ($10^5$ K) at $z \sim 7$. Galaxy formation in such low-mass haloes is expected to be very inefficient, owing to a strong reliance on molecular cooling. If the UVLF remains steep into the regime of UFDs, then there should be a substantial population of UFDs observable in the LG (e.g. Boylan-Kolchin et al. 2014, 2015; Lapi et al. 2017). However, $\lesssim 10$ per cent of the predicted number of extremely low mass galaxies are known to exist in the LG (e.g. see updates to McConnachie 2012).

While environmental effects (e.g. efficient destruction of satellites, dwarf–dwarf mergers, stellar stripping) could alleviate some tension, these mechanisms do not appear efficient enough to resolve the discrepancy (e.g. Kirby et al. 2013; Deason et al. 2014; Garrison-Kimmel et al. 2017). Furthermore, the overabundance of LG dwarfs is not limited to the faintest UFDs, as it is known to persist in the ‘classical’ dwarf regime (Boylan-Kolchin et al. 2015), which is thought to be observationally complete (e.g. Koposov et al. 2008).

Even more challenges arise if (i) the faint end of the UVLF approaches $\alpha = -2.4$ (i.e. many more faint galaxies); and/or (ii) such low-mass galaxies have a low star formation duty cycle (e.g. $\sim 10$ per cent; Wyithe et al. 2014). In the latter case, 90 per cent of the haloes would be in the ‘off’ state at any given time, and thus have reduced UV luminosities. Effectively, this results in higher luminosity galaxies hosted in even lower mass haloes, assuming a canonical SMH.

3.2 Minimizing the flux contribution of ultra-faint dwarfs

Up to this point, we have considered the consequences of extrapolating a Schechter UVLF into the regime of UFDs. However, several numerical simulations of galaxy formation predict a turnover in the UVLF, decreasing the predicted number of very faint galaxies in the early Universe (e.g. Jaacks et al. 2013; O’Shea et al. 2015; Gnedin 2016; Liu et al. 2016; Ocvirk et al. 2016; Yue et al. 2016; Finlator et al. 2017). Although details vary, the common threads among these simulations are that not all low-mass haloes necessarily host a galaxy and that baryonic effects internal to the galaxies (e.g. supernova feedback, radiation pressure) can significantly affect galaxy formation in low-mass haloes. Alternatively, a turnover in the high-$z$ UVLF is consistent with models that suppress or eliminate small-scale structure (e.g. warm dark matter; Schultz et al. 2014; Dayal et al. 2015). A broken luminosity function at high $z$ is also necessary in order to avoid dramatically overproducing UFDs and even classical dwarfs in the LG (Boylan-Kolchin et al. 2014, 2015).

Fig. 4 illustrates the effects of two plausible UVLF turnovers. For simplicity, we focus only on the $z = 7$ case and adopt analytic UVLFs that turn over from Jaacks et al. (2013) and Boylan-Kolchin et al. (2015). The UVLF from the latter study has $\alpha \sim -2$ for $M_{\text{UV}} < -13$ and $\alpha \sim -1.2$ for $M_{\text{UV}} \geq -13$ and is designed to reproduce $z = 0$ LG dwarf galaxy counts. We have tuned the UVLF from Jaacks et al. (2013) to match that of Boylan-Kolchin et al. (2015).

The bottom panel of Fig. 4 shows the cumulative fraction of UV flux for the UVLFs in the top panel. The decreased number density for UFDs reduces their UV flux contribution to $\lesssim 10$ per cent. We emphasize that this figure provides only an illustration of the effects of a turnover in the UVLF and it is not necessarily correct in detail. Furthermore, there is already tentative evidence that the UVLF remains steep at $z \sim 6$ down to at least $M_{\text{UV}} \sim -12.5$ (Livermore et al. 2016), which might be in tension with our selected turnover parameters (though see Bouwens et al. 2016).

Beyond matching local galaxy counts and reducing the contribution of UFDs to reionization, any turnover in the UVLF also affects the SMH relation. The UVLFs with a turnover in Fig. 4 place $M_{\text{UV}}(z = 7) = -3.1$ UFDs in haloes with $M_{\text{halo}}(z = 7) = 2 \times 10^9 M_\odot$ instead of $\sim 10^8 M_\odot$. Such a turnover therefore places the faintest...
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4 SUMMARY

By combining the stellar fossil record of known UFDs in the LG with population synthesis modelling, we have demonstrated that star-forming galaxies with UV luminosities as faint as \( M_{UV} = -3 \) to \(-6 \) must have existed during the epoch of reionization (\( z \approx 6-10 \)). We explored the implications of this result under two possible scenarios, which can be summarized as follows:

If the measured high-redshift UVLFs with steep faint-end slopes are valid into the luminosity regime of UFDs:

(i) Galaxies fainter than \( M_{UV} = -10 \) contribute \( >50-80 \) per cent of the total UV flux from galaxies during reionization.

(ii) Galaxies can still power reionization with escape fractions that are \( >50 \) per cent lower then currently assumed.

(iii) The ancestors of UFDs must have been hosted in haloes with \( M_{\text{halo}}(z \approx 7) \approx 10^9 \, M_\odot \), well below the virial mass that corresponds to the atomic cooling limit.

(iv) There should be \( \sim 10 \) times more galaxies around the MW with luminosities as bright as Draco (\( M_V = -8.8 \)).

If the high-\( z \) galaxy UVLF turns over at \( M_{UV}(z \approx 7) \approx -13 \):

(i) UFDs do not contribute substantially to reionization at \( z \lesssim 8 \).

(ii) There is no number galaxy count tension in the LG.

(iii) UFDs live in haloes more massive than the virial mass associated with the atomic cooling limit.

A complete census of LG UFDs has the promise to provide a robust constraint on the faint end of high-\( z \) UVLFs. Even with the current census, a scenario in which the high-\( z \) luminosity function is sharply truncated at magnitudes significantly brighter than \( M_{UV} \sim -3 \) to \(-6 \) is inconsistent with the existence of UFDs in the LG. Thus, it appears unavoidable that the galaxy luminosity function extends, without a sharp truncation, to luminosities that are \( \sim 10,000 \) times fainter than the blank-field UDF limits.

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Figure 4. Top panel: a comparison between the UVLFs at \( z \approx 7 \) with and without turnovers. The steep UVLF (black; \( \alpha \sim -2 \)) is from Finkelstein et al. (2015), while the other curves show models from Boylan-Kolchin et al. (2015, orange) and Jaacks et al. (2013, magenta). Bottom panel: the fraction of UV flux at \( z \approx 7 \) for each of the UVLFs shown in the top panel, when integrated to \( M_{\text{min}} = -3.1 \). A break or turnover in the UVLF at \( M_{UV} = -13 \) significantly reduces the flux contribution from UFDs.

Galaxies in haloes above the atomic cooling limit, resolving another possible tension implied by a steep UVLF.
