The Long Faint Tail of the High-Redshift Galaxy Population

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Abstract. We study the properties of very faint, sub-$L^*$ Lyman break galaxies at $z \sim 2-5$ — thus far a largely neglected but numerically and energetically very important population. We find that the LBG luminosity function undergoes luminosity-dependent evolution: the number of luminous galaxies remains constant while the number of faint ones grows with time. The total UV luminosity density increases with cosmic time from at least $z \sim 5$ until reaching a peak or a plateau around $z \sim 2$ — behaviour that is governed by the sub-$L^*$ galaxies in the LF's "faint tail". Using broadband SED fitting we find a nearly-linear relationship between SFR and galaxy stellar mass at $z \sim 2$. A typical $L^*$ LBG at $z \sim 2$ shows a stellar mass of $\sim 10^{10} M_\odot$, remarkably similar to the bimodality mass at low redshift. This similarity suggests that the mechanisms responsible for the galaxy bimodality at low-$z$ may have also been at play at $z \sim 2$.

1. Introduction

Until very recently, studies of $z>1$ galaxies have focused primarily on luminous, vigorously star-forming objects such as submillimetre sources or $L \sim L^*$ LBGs that are forming stars at rates of 10s or 100s $M_\odot/yr$. Such studies have largely neglected the less glamorous but far more numerous faint, sub-$L^*$ galaxies that are forming stars at much lower rates. Although individually faint, these sub-$L^*$ objects are very numerous and so collectively they generate more than half the total UV luminosity density of the universe at high redshift. They are, thus, extremely important contributors to the story of star formation and metal enrichment in the early Universe. Moreover, the presence of a break at $L^*$ in the galaxy LF suggests that galaxies below $L^*$ differ substantially from those above it. Because of this, our understanding of the mechanisms that drive galaxy evolution at high redshift may profit from comparing the properties of the better-studied luminous ($L \gtrsim L^*$) objects with those of the neglected sub-$L^*$ galaxies. This paper summarizes the results of our recent work aimed at understanding these hitherto neglected, individually modest but collectively very important objects. They are the long faint tail of the high-$z$ galaxy population.

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2. Luminosity function and luminosity density

2.1. Data

The shape of the galaxy LF bears the imprint of galaxy formation and evolution processes. We study the global statistics of sub-$L^*_{z=3}$ galaxies at $z\sim2$, 3, 4, and 5 using two deep, large-area, multi-field imaging surveys.

At $z\sim2$, 3, and 4 we use the Keck Deep Fields (KDF) of Sawicki & Thompson (2005, 2006a, b). The KDF use the very same $U_{gr}IR$ filter set and color-color selection criteria as are used in the well-known work of Steidel et al. (1999, 2003, 2004). However, in contrast to the Steidel et al. work, the KDF reach $R_{lim}(AB)=27$, which is 1.5 mag deeper than the Steidel et al. surveys and significantly below $L^*_{z=3}$; even at $z\sim4$ we reach 2 mag fainter than $M^*$. The KDF have an area of 169 arcmin$^2$ divided into three spatially independent regions on the sky that allow us to monitor the effects of cosmic variance. The $U_{gr}IR$ filters and color-color selection commonality with the work of Steidel et al. lets us confidently select very faint, sub-$L^*_{z=3}$ galaxies at $z\sim2$, 3, and 4 by relying on their extensive spectroscopic characterization of sample selection. It also allows us to confidently combine our data with theirs, thereby for the first time consistently spanning such a large range in galaxy luminosity at high redshift.

Our $z\sim5$ work is based on very deep $VI_{cz}$ imaging of two Subaru Suprime-Cam fields presented in Iwata et al. (2006, 2007). These data are wider and deeper than earlier work we presented in Iwata et al. (2003): they now span a total of 1,300 arcmin$^2$ divided over two fields with $z'_{lim}(AB) = 26.5$ and 25.5. The large area covered by these data is essential for determining the abundance of the rare, luminous objects, while at the same time the depth of the data gives us the necessary ability to probe below $L^*$ in the LF. We use $VI_{cz}$ Lyman break selection to select $z\sim5$ galaxies and our ongoing spectroscopic program has already confirmed a number of $z\sim5$ galaxies, validating our $z\sim5$ color-color selection technique (Ando et al. 2004; Iwata et al. 2007).

2.2. The differentially evolving luminosity function

We find that the luminosity function of high-$z$ galaxies undergoes evolution that is differential with luminosity. As Fig. 1(a) shows, the bright end of the LF remains virtually unchanged, but the faint end evolves from $z\sim5$ to at least $z\sim3$. Our tests show that it is highly unlikely that this observed differential evolution is due to some systematic effect such as selection bias, our modeling of the survey volume, etc. (for details see Sawicki & Thompson 2006a). The effect is also quite significant — the statistical probability that the $z\sim4\rightarrow3$ evolution is not differential with luminosity is only 1.5%, and the result is even more robust for $z\sim5\rightarrow3$. We conclude that the differential, luminosity-dependent evolution is very likely real. If so, it must reflect some real, intrinsic evolutionary differences between faint and luminous LBGs. Understanding what causes these differences will give us insights into what drives galaxy evolution at high redshift.

2.3. Luminosity and star formation rate densities

The importance of the LF’s faint end extends into measurements of the cosmic luminosity density and the cosmic star formation rate that is often derived from it. For reasonable faint-end slopes of the LF the bulk of the luminosity density
resides in galaxies that are fainter than $L^*$ and it is only with deep, multi-field, large-area surveys such as ours that it is possible to reliably measure the contribution of this dominant population.

Figure 1(b) shows the evolution of the UV luminosity density using data from GALEX (Arnouts et al. 2005; Wyder et al. 2005), Keck Sawicki & Thompson (2006b), and Subaru (Iwata et al. 2007). The total UV luminosity density, i.e., luminosity density due to galaxies of all luminosities, rises from early epochs, $z \geq 5$, experiences either a plateau or a broad peak at $z \sim 3–1$, and then a decline to $z=0$. This behavior of the total luminosity density is dominated not by luminous galaxies, but by sub-$L^*_{z=3}$ objects. Indeed, it is galaxies within the rather narrow luminosity range $L=(0.1–1)L^*_{z=3}$ that dominate at high redshift, $z \sim 2–5$, and it is the rapid evolution of this population that drives the evolution in the total UV luminosity density. Thus far, this faint population has been largely neglected in high-$z$ follow-up studies which have focused on $L \gtrsim L^*_{z=3}$ LBGs. In contrast to $z \geq 2$, at lower redshifts, $z \leq 1$, the total UV luminosity density is dominated by very faint galaxies with $L<0.1L^*_{z=3}$. The $L=(0.1–1)L^*_{z=3}$ galaxies that dominated at $z \geq 2$ are still important but no longer dominant. This switch in the luminosity of the galaxies that dominate the total luminosity density is reminiscent of galaxy downsizing, although the effect we see so far is a downsizing in UV luminosity rather than galaxy mass.
3. Physical properties from SED fitting of sub-\(L^*\) galaxies at \(z\sim2\)

3.1. The galaxy sample and SED fitting technique

As we have discussed above, sub-\(L^*\) LBGs dominate over their more luminous cousins, but evolve differently from them as a population. We now wish to know what makes them physically different. We attempt to address this issue through broadband spectral energy distribution (SED) studies. Unlike in the LF work, here we do not need large samples of objects but instead must have deep multiwavelength photometry that spans from the UV to beyond the Balmer break in the rest frame. We need to go particularly deep because we wish to study galaxies significantly fainter than \(L^*\) at \(z>2\). No spectroscopic samples of such very faint LBGs currently exist and so we must use photometric redshifts.

Our first foray into this area is at \(z\sim2\) and uses the HST WFPC2+NICMOS \(U_{300}B_{450}V_{606}I_{814}J_{110}H_{160}\) data of the northern Hubble Deep Field (HDF). These data are ideal for us as they are very deep, include the \(U\)-band imaging essential for selecting \(z\sim2\) LBGs, and span the age-sensitive Balmer break at the target epoch.

After smoothing the multiband images to a common PSF and obtaining SExtractor (Bertin & Arnouts 1996) photometry, we constructed a \(U\)-band drop-out sample using the LBG color-color selection criteria defined by Steidel et al. (1996) for the HDF. We then applied a photometric redshift cut, \(1.8\leq z_{\text{phot}}\leq2.6\), where the photometric redshifts are determined as part of the SED-fitting procedure (see below). The lower limit of this photo-z cut eliminates potential low-\(z\) interlopers and the higher limit excludes high-\(z\) LBGs for which the \(U_{300}B_{450}V_{606}I_{814}J_{110}H_{160}\) filter set does not span the crucial, age-sensitive Balmer break. This procedure (two-color selection followed by a photo-z cut) is very similar to the procedure (two-color selection followed by spectroscopy) used by Steidel et al. in their work. Our resulting sample of \(\sim70\) objects has a mean redshift \(\overline{z}_{\text{phot}}=2.3\) and in other ways also closely mimics the BX samples of Steidel et al. (2003) and Shapley et al. (2005). However, it contains much fainter galaxies, reaching down to \(R(AB)=27\) [1].

Our SED fitting procedure follows the now well-established approach first developed for LBGs by Sawicki & Yee (1998) and subsequently used by many others (e.g., Papovich et al. 2001; Shapley et al. 2001, 2005; Iwata et al. 2005). We compare the observed \(B_{450}V_{606}I_{814}J_{110}H_{160}\) galaxy photometry with predictions of Bruzual & Charlot (2003) spectral synthesis models attenuated by Calzetti et al. (2000) dust. We fix metallicity and star formation history and fit for burst age, star formation rate, stellar mass, dust reddening, and redshift. While for brighter samples redshifts are usually constrained from spectroscopy, here we must keep redshift as a free parameter. However, our tests as well as previous experience with this approach (Sawicki 2002; Hall et al. 2001) show that lack of spectroscopic redshifts does not significantly affect the results.

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[1] As in Steidel et al. (1996), the \(R\) magnitude is defined via averaging the \(V_{606}\) and \(I_{814}\) fluxes.

[2] While \(U_{300}\) is essential for selecting our LBG sample, we omit it from the SED fitting to avoid contaminating our SED analysis with the stochastic effects of intergalactic hydrogen absorption.
3.2. A mass-SFR relation and a characteristic mass

Figure 2a shows that the bulk of the galaxies in our HDF sample follows a relation between stellar mass and UV luminosity and this relation extends into the brighter galaxies of Shapley et al. (2005). There appears to be good correlations between stellar mass and UV luminosity (Fig. 2a) and stellar mass and SFR (Fig. 2b). Outliers in both samples turn out to be galaxies with constant-SFR best-fit ages apparently older than the age of the Universe at $z$=2.3 (triangles) and galaxies with very young ages age $\lesssim$30Gyr (squares). However, most objects show a fairly tight correlation which can be described by the relation $\log(M_{\text{stars}}/M_\odot) = 9.0 + 0.86 \log[SFR/(M_\odot\text{yr}^{-1})]$ (solid line in Fig. 2b). The inclusion of the outliers in the fit does not significantly affect this result.

The $L^*$ knee in the $z\sim2.2$ LF ($M_{1700\lambda}^{*}=-20.6$ at $z\sim2.2$: Sawicki & Thompson, 2006a) corresponds to a stellar mass $M_{\text{stars}}(L^*)\sim10^{10} M_\odot$ (Fig 2a). This $z\sim2$ characteristic mass is remarkably similar to the $3\times10^{10} M_\odot$ characteristic mass that at low redshift marks the transition between the two distinct galaxy “bimodality” families (Kauffmann et al. 2003). This similarity of characteristic masses suggests that the processes (see, e.g., Dekel & Birnboim 2006) responsible for the observed galaxy bimodality at low $z$ may have also been operating at $z\sim2$. Moreover, the near-unity slope of the logarithmic relation between stellar mass and UV luminosity (Fig. 2a) suggests that the bulk of the detectable stellar mass in $z\sim2.2$ LBGs resides in the thus-far poorly studied galaxies with $L^* > L > 0.1L^*$, just as does the bulk of the total UV luminosity density.

The outliers with extremely young fit ages (square symbols) are apparently either undermassive for their SFRs or overluminous for their masses. In the former case they may move up onto the mass-SFR relation as they age; in the
latter they could be experiencing strong star-forming bursts that dramatically elevate their normally low luminosities. Outliers with very old best-fit ages (triangles), are also consistent with variable star formation histories: constant star formation histories tend to yield the largest ages (e.g., Sawicki & Yee [1998, Papovich et al. [2001]) and thus the old ages here may simply be telling us that star formation in these galaxies was more intense in the past. All these scenarios advocate that at least some \( z \sim 2 \) LBGs, both faint and luminous, have variable star formation histories — consistent with one of the scenarios proposed by Sawicki & Thompson (2006a) to explain the evolving LBG luminosity function.

4. Concluding remarks

The thus-far largely unexplored sub-\( L^* \) LBGs dominate the UV luminosity density of the universe at \( z > 2 \). Moreover, their stellar masses appear to correlate with UV luminosities down to very faint magnitudes at least at \( z \sim 2 \) and so, just as they dominate the UV luminosity density, these objects may also contain a substantial fraction of the formed stellar mass by that redshift. At the same time, however, the differentially-evolving luminosity function suggests that these sub-\( L^* \) LBGs differ substantially from their more luminous cousins. It is not yet clear what mechanism is behind this differential evolution, but the bursty nature of at least some of the \( z \sim 2 \) galaxies means that changes in the timescales of star-burst episodes may play a role. We will address this and other issues as we extend our SED-fitting and other differential studies to higher redshifts.

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