The Star Formation Density at z~7

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Abstract. Near-infrared VLT data of the GOODS-South area were used to look for galaxies at z~7 down to a limiting magnitude of (J+Ks)_{AB}=25.5. No high-redshift candidates were detected, and this provides clear evidence for a strong evolution of the luminosity function between z=6 and z=7, i.e. over a time interval of only ~170 Myr. Our constraints provide evidence of a significant decline in the total star formation rate at z=7, which must be less than 40% of that at z=3 and 40-80% of that at z=6. The resulting upper limit to the ionizing flux at z=7 is only marginally consistent with what is required to completely ionize the Universe.

1. Introduction

In recent years, a large effort was put into obtaining a clear picture of the evolution of the star formation activity along the Hubble time. Observations are approaching the interesting redshift range between z=6 and z=10 where current cosmological models expect to find the end of the reionization period and the “starting point” of galaxy evolution (e.g., Stiavelli, Fall & Panagia 2004).

Most high-redshift galaxies were selected by the dropout technique, i.e., by detecting the spectral break in the UV continuum blueward of the Lyα due to intervening Lyα-forest. This technique is mainly sensitive to high-redshift UV-bright galaxies, commonly named Lyman-Break Galaxies (LBGs). The use of different filters allows the selection of different redshift ranges. At z>6 the use of near-IR images is mandatory, which makes detection much more difficult. Deep J-band images from HST/NICMOS exist, but their field-of-view is limited to a few sq.arcmin. Larger fields can be observed by ground-based telescopes, but at the expense of lower spatial resolution and brighter detection limits.

Recently, Bouwens & Illingworth (2006) looked for galaxies at z~7 in a few deep NICMOS fields covering ~19 sq.arcmin. They detected four possible z~7 objects, while 17 were expected based on the z=6 LF. This result point toward the existence of a strong reduction in the LF with increasing redshift at z>6. In contrast, Richard et al. (2006) examined two lensing clusters and derived a star formation density (SFD) well in excess of the one at z=3, hinting at large amounts of star formation activity during the first Gyr of the universe. The faintness of the high-redshift candidates of the previous studies imply that their redshifts cannot be spectroscopically confirmed with the current generation of telescopes. Here we present a study aimed at detecting brighter z=7 objects in a large field, in order to measure the cosmic star-formation density at this redshift.
Figure 1. Color-color selection diagram for \( z > 7 \) galaxies. The solid lines show the variation in the colors with redshift expected for local galaxies (Mannucci et al. 2001) and galaxy models by the Bruzual & Charlot (2003) with three different amounts of extinctions \((E(B-V)=0.0, 0.3, \text{ and } 0.6)\). Thin and thick lines show the expected colors for galaxies below and above \( z=7 \), respectively. Stars show the expected positions of Galactic brown dwarfs (ranging from T8 to L1, from left to right). Small dots show the galaxies detected in the GOODS-South in all three bands, while the arrows show the positions of the objects undetected in K. The dashed line shows the color threshold. Above this threshold only objects with no counterparts either in the HST/ACS filters \(b_{435}, v_{606}, \text{ and } i'_{775}\) or in the sum \(b_{435}+v_{606}+i'_{775}\) image are shown. Large solid dots with numeric label show the measured colors of two brown dwarfs.

2. Observations, object catalog and color selection

The main catalog is based on ESO/VLT J and Ks data of the GOODS-South field covering 133 sq.arcmin. The typical exposure time is 3.5h in J and 6h in K, with a seeing of about 0.45″ FWHM. To improve detectability of blue objects we used the J+Ks sum image to build the main object catalog. The average 6\(\sigma\) AB magnitude limit inside a 1″ aperture is 25.5, estimated from the statistics of the sky noise. The main catalog comprises about 11,000 objects.

We selected drop-out objects that are undetected (<1\(\sigma\)) in \(i'_{775}\) and in all bluer bands and that have \(z'-J>0.9\) and \(J-Ks<1.2(z'-J)-0.28\) as measured in 1″ apertures, as shown in Figure 1. It is evident that the use of near-IR colors alone is enough to exclude low/intermediate galaxies, but not to distinguish true \(z\sim7\) star-forming galaxies from high-z QSOs or Galactic brown dwarfs.

Two objects show colors that are compatible with star-forming galaxies at \(z>7\). Through detailed analysis of their morphology and near/mid-IR colors, as well as through spectroscopic information, these two candidates were identified as Galactic brown dwarfs (for details, see Mannucci et al., 2006) As a consequence, no \(z=7\) object is present in the survey field above our detection limit.
3. Evolution of the luminosity function and of the cosmic star-formation density

The detection of no \( z > 7 \) objects in the field can be used to place an upper limit to the LF of these objects. To do this we have computed the effective sampled volume as a function of the absolute magnitude of the objects taking into account the effect of redshift on both colors and brightness of the objects. We use the concordance cosmology \((h_{100}, \Omega_m, \Omega_\Lambda) = (0.7, 0.3, 0.7)\). The redshift sensitivity of our selection method starts at about \( z = 6.7 \), followed by a peak at \( z = 7 \) and a shallow decrease towards high redshifts. The limiting apparent magnitude (\( \sim 25.5 \)) corresponds, at \( z = 7 \), to an absolute magnitude \( M(1500) = -21.4 \), i.e., to \( \text{SFR} \sim 20 \text{M}_\odot/\text{yr} \) (Madau et al. 1998). This means that we can sample the bright part of the LF of LBG at any redshift down to \( \sim 1-2 \) \( \text{L}^* \).

In the left panel of figure 2 we show the \( 1\sigma \) upper limits to the density of objects, compared with the LF of the LBGs at \( z = 6 \) from Bouwens et al. (2006) and at \( z = 3 \) obtained by Steidel et al. (2003). Our upper limits imply an evolution of the LF from \( z = 6 \), even if only 170 Myr have passed since then. In the no-evolution case, in fact, we would expect to detect 5.5 objects, with a Poisson probability of no detection smaller than 0.5%.

Using a confidence level \( \text{CL}=90\% \) and assuming density evolution of the LF, we found that the normalization of the LF at \( z = 7 \) must be at most 40% of that at \( z = 6 \). Assuming luminosity evolution we obtain that the objects must be at least 0.22 mag brighter at \( z = 6 \) than at \( z = 7 \). This evolution corresponds to a reduction of 20% in the total SFD, obtained by integrating the LF assuming a constant faint-end slope \( \alpha \).

Our limits can be compared with the LF at \( z = 3 \) (Steidel et al. 2003). Assuming luminosity evolution we obtain a shift of \( L^* \) about 0.9 mag, corresponding to \( \text{SFD}(z=7)/\text{SFD}(z=3)=0.42 \), a reduction of more than a factor of 2. A pure density evolution would require \( \text{SFD}(z=7)/\text{SFD}(z=3)=0.05 \).

4. The evolution of the star formation activity

In the right panel of figure 2 we show the values of the SFD obtained by integrating the observed LFs above a given luminosity threshold and converting to SFR using Madau et al. (1998). The most interesting quantity, the total SFD at each redshift, would be obtained by using a very low luminosity threshold. Unfortunately, this would introduce large uncertainties due to the unobserved part of the LF at low luminosities. For example, for a faint-end slope of the LF \( \alpha = -1.6 \), about half of the total SFD takes place in galaxies below 0.1\( L^* \), which are usually unobserved. This implies that a correction of about a factor of two is needed to obtain the total SFD from the observed part of the LF. To avoid this additional uncertainty, it is common to refer to the SFD derived from galaxies that where directly observed or by using a small extrapolation of the LF.

The right panels of figure 2 show the SFD as obtained by integrating the observed LFs with two different lower limits. In the upper panel we show the results when considering, at any redshift, the same range of absolute magnitudes (\( M(1500) > -19.32 \)), i.e., limiting the luminosity to above 20% of the \( L^* \) magni-
Figure 2.  

Left: The limits to the density of $z=7$ galaxies (connected downward arrows) are compared with the LFs of LBGs at $z=3$ (dashed line, Steidel et al. 2003) and $z=6$ (solid line, Bouwens et al. 2006) The upper limit with a cross corresponds to the object detected by Bouwens et al. (2004) in the HUDF and considered to be at $z \sim 7$.

Right: Cosmic star formation as derived from rest-frame UV observations and with no correction for dust extinction. The upper panel shows the results of integrating the LF for $L > 0.2L^*(z=3)$, the lower panel for $L > 0.2L^*(z)$ (see text). The black dot with error bars is the upper limit from the present work and is the average the average between the two extremes of pure luminosity and pure density evolution, while the upper value corresponds to pure luminosity evolution. The empty dots are from literature (see Mannucci et al., 2006, for details). The diamonds at $z=7.5$ and $z=10$ are from Bouwens et al. (2004, 2005). The dotted lines shows an empirical fit to the data in the upper panel, the dashed line to those in the lower panel.

tude derived by Steidel et al. (1999) for their LBGs at $z=3$ ($L > 0.2L^*(z=3)$). The derived SFD is directly related to the total SFD in the case of pure density evolution, as the fraction of SFD from galaxies below the threshold would be constant. The use of the absolute limits of integration is very common (see, for example, Bouwens et al. 2006) The resulting SFD appears to vary rapidly, increasing by more than a factor of 30 from $z=0.3$ to $z=3$ and then decreasing by a factor of 2.2 to $z=6$ and $\sim 4$ to $z=7$.

In the case of luminosity evolution, the use of a constant limit of integration results in considering a variable fraction of LF. For example, Arnouts et al. (2005) measured the UV LF at low redshift and found a strong luminosity evolution, with $M^*=-18.05$ at $z=0.055$ and $M^*=-20.11$ at $z=1.0$. In this case, at low redshift the limit of integration used above ($M(1500) > -19.32$) is even brighter than $L^*$ and only a small fraction of the LF is integrated to obtain a
value of the SFD. This is the reason that the upper panel of figure 2 shows such a strong evolution at low redshift. In the lower panel of figure 2 we use a variable limit of integration, set to be $0.2L^*(z)$ at each redshift. This is more suitable to reproducing the total cosmic SFD, as the luminosity evolution appears to dominate both at low (Arnouts et al. 2005) and at high redshifts (Bouwens et al. 2006). In this case, the obtained evolution is much milder with an increase of a factor of 5 from $z=0.3$ to $z=3$ and a decrease of $\sim 1.4$ to $z=6$ and $\sim 2.5$ to $z=7$. The resulting values of the UV luminosity density and of the SFD can be found in Mannucci et al. (2006).

All the data in figure 2 are derived from UV observations and, as a consequence, they are very sensitive to dust extinction, as discussed by a large number of authors. Variation in the dust content along the cosmic age is one of the effects that could contribute to shaping the observed evolution of the SFD. The typical color of $z=6$ LBGs, represented by the UV spectral slope $\beta$, is bluer at $z=6$ ($\beta = -2.2$, Stanway et al. 2005) than at $z=3$ ($\beta = -1.5$, Adelberger & Steidel 2000), pointing towards a reduction in average extinction at high redshift of about a factor of two. As a consequence, the observed reduction in the SFD cannot be due to an increase of the dust content. Actually, considering this effect would make the increase of SFD with cosmic time even more pronounced.

As we observe the bright part of the LF, we cannot exclude that the reduction in the number density of bright galaxies is not associated with an increase in that of the faint galaxies. If, for example, both $\Phi^*$ and $L^*$ vary together so that $\Phi^*L^*$ remains constant, the resulting total SFD also remains constant. We cannot exclude this effect, even if the upper limits to the galaxies with $L \sim L^*$ from Bouwens et al. (2004) tend to exclude this possibility.

5. Consequences on reionization of the primordial universe

It is widely accepted that high redshift starburst galaxies can contribute substantially to the reionization of the universe. Madau et al. (1999) estimated the amount of star formation needed to provide enough ionizing photons to the intergalactic medium. By assuming an escape fraction of the photons $f_{\text{esc}}$ of 0.5 and a clumping factor $C$ of 30 (Madau et al. 1999), we find that at $z=7$ the necessary SFD is

$$\text{SFD(needed)} \sim 7.8 \times 10^{-2} \ M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$$

The observed total amount of SFD derived from UV observations can be derived by integrating the observed LF down to zero luminosity. Assuming luminosity evolution and integrating the LF down to $0.01L^*$, we obtain

$$\text{SFD(observed)} = 2.9 \times 10^{-2} \ M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$$

where about half of this comes in very faint systems, below $0.1L^*$. This value can be increased up to $\sim 5 \times 10^{-2} M_\odot/\text{yr}/\text{Mpc}^{-3}$ assuming the steeper faint-end slope on the LF ($\alpha = -1.9$) compatible with the data in Bouwens et al. (2006).

The uncertainties involved in this computation are numerous and large for both SFD(needed) and SFD(derived). Nevertheless, the amount of ionizing photons that can be inferred at $z=7$ from observations is less or, at most, similar
to the needed value. A measure of the SFD at even higher redshifts or tighter constraints to the faint-end slope of the LF at $z=6$ can significantly reduce these uncertainties and can easily reveal that it falls short of the required value.

6. Conclusions

The existing multi-wavelength deep data on the large GOODS-South field allowed us to search for $z=7$ star-forming galaxies by selecting $z'$-dropouts. The accurate study of the dropouts in terms of colors, morphology, and spectra allows us to exclude the presence of any $z=7$ galaxy in the field above our detection threshold. We used this to derive evidence for the evolution of the LF from $z=7$ to $z=6$ to $z=3$, and to determine an upper limit to the global star formation density at $z=7$. These limits, together with the numerous works at lower redshifts, point toward the existence of a sharp increase of the star formation density with cosmic time from $z=7$ to $z=4$, a flattening between $z=4$ and $z=1$, and a decrease afterward. The ionizing flux from starburst galaxies at $z=7$ could be too low to produce all the reionization.

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