THE POSSIBLE DETECTION OF COSMOLOGICAL REIONIZATION SOURCES

M. Stiavelli, S. Michael Fall, and N. Panagia
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218
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ABSTRACT

We compare the available catalogs of \( z \approx 6 \) galaxies in the Hubble Ultra-Deep Field and in the Great Observatories Origins Deep Survey with the expected properties of the sources of cosmological reionization from our previous theoretical study. Our approach is based on the mean surface brightness of the sources required for reionization and depends on relatively few undetermined parameters. We find that the observed mean surface brightness of galaxies at \( z \approx 6 \) is sufficient for reionization, provided that the sources are composed of hot metal-free or metal-poor stars, regardless of whether reionization occurs over a short or long interval of redshift. The broad agreement between the new observations and our predictions suggests that we may have detected the sources responsible for some or even all of the reionization of hydrogen.

Subject headings: cosmology: observations — cosmology: theory — early universe

1. INTRODUCTION

The reionization of the intergalactic medium (IGM) was undoubtedly one of the most significant events in cosmic history. It completely changed the opacity of the universe to ionizing radiation and may also have influenced the formation and evolution of galaxies and other structures (see, e.g., Loeb & Barkana 2001). The absence of strong Gunn-Peterson Ly\( \alpha \) absorption in the spectra of distant quasars indicates that reionization was complete by \( z \approx 6 \) (Becker et al. 2001; Fan et al. 2002; White et al. 2003), while the polarization of the cosmic microwave background (CMB) radiation indicates that it began at higher redshifts (Spergel et al. 2003). A major goal of extragalactic astronomy is to detect and characterize the sources of UV radiation responsible for reionization.

In a previous paper, we outlined a method to guide and interpret searches for the reionization sources with existing and planned telescopes (Stiavelli et al. 2004, hereafter Paper I). Our work builds on several important papers in this field, including those by Miralda-Escudé & Rees (1998) and Madau et al. (1999). We consider the same physical processes as previous authors, but we focus on low-metallicity sources (Population II and III stars), which are more efficient ionizers and are perhaps more natural at high redshifts (e.g., Malhotra & Rhoads 2002). We ignore active galactic nuclei (AGNs) because constraints from the X-ray background indicate that they make a relatively small contribution to reionization (Dijkstra et al. 2004). We express our results in terms of the mean surface brightness of the reionization sources instead of their volume emissivity or star formation density because this allows a more direct comparison with observations. We focus on the expected location of the sources in a plot of mean surface number density against apparent magnitude. Only a moderately narrow band in this diagram is allowed by the demands of producing enough ionizing radiation but not too many heavy elements (for stellar sources).

We showed that the existing deep surveys with the Hubble Space Telescope (HST), such as the Hubble Deep Fields (HDFs; Williams et al. 2000) and the Great Observatories Origins Deep Survey (GOODS; Giavalisco et al. 2004), do not probe far into the allowed part of this diagram, while future deep surveys with the James Webb Space Telescope (JWST) will do so easily. We also pointed out that there was a reasonable chance of detecting the reionization sources with the then-planned HST Ultra Deep Field (UDF; S. Beckwith et al. 2004, in preparation). This observing program has now been completed, the data have been released, and several papers have appeared with catalogs of sources (Bouwens et al. 2004; Bunker et al. 2004). Here, we combine the available UDF and GOODS observations with our previous theoretical expectations to search for the reionization sources. Throughout this Letter, we adopt values of the cosmological parameter derived from the Wilkinson Microwave Anisotropy Probe (WMAP): \( \Omega_\Lambda = 0.732, \Omega_m = 0.268, \Omega_b = 0.044, \) and \( H_0 = 71 \) km s\(^{-1}\) Mpc\(^{-1}\) (Spergel et al. 2003).

2. MODELS

Our general method is applicable to a wide variety of reionization sources. For specific predictions, however, we focus on sources composed of either metal-free stars (hereafter Population III) or metal-poor stars (\( 10^{-3} \leq Z/Z_\odot \leq 10^{-2} \), hereafter Population II). We approximate the spectral energy distributions of these sources by blackbodies with temperatures of \( 10^5 \) K for Population III and \( 5 \times 10^4 \) K for Population II. These effective temperatures are most appropriate for stellar populations with top-heavy initial mass functions (IMFs; dominated by stars more massive than \( \sim 30 M_\odot \)). Since Population III stars are hotter than Population II stars, they produce more ionizing photons for a given flux at longer wavelengths. In this sense, Population III stars are also more efficient ionizers than AGNs.

Figure 1 shows the expected cumulative mean surface number density of reionization sources as a function of their apparent AB magnitude in the nonionizing UV continuum at a rest-frame wavelength of 1400 Å. Here we have assumed that the comoving volume density of the sources is constant over the range of redshifts 5.8 \( \leq z \leq 6.7 \) spanned by \( i \)-band dropouts in the UDF and GOODS (see § 3). The luminosity function of the sources is assumed to have the Schechter form, parameterized by its knee \( M_\star \) and slope \( \alpha \). For reference, the Lyman break galaxies at \( z = 3 \) have \( M_\star,1400 = -21.2 \) and \( \alpha = 1.6 \). (Steidel et al. 1999; Yan et al. 2002). These are the parameters adopted for the top panels of Figure 1. The middle panels have a brighter knee \( (M_\star,1400 = -23.2) \), and the bottom panels have a steeper slope \( (\alpha = 1.9) \). The predictions in the left panels are for Population III stars; those in the right panels are for
The specific predictions shown in Figure 1 assume that reionization is complete at $z = 6$. This is supported strongly by the Lyα absorption of $z \sim 6$ quasars and by a variety of theoretical arguments and hydrodynamical simulations (Haiman & Holder 2003; Gnedin 2004). The mean surface brightness required for reionization also depends on the interval of redshift over which the sources are active. Here we concentrate on the interval $\Delta z \approx 1$ just above $z \approx 6$. This closely matches the interval spanned by $i$-band dropouts and is marginally compatible (at 2 $\sigma$ confidence) with the measured CMB polarization (Spergel et al. 2003). The interval $\Delta z \approx 1$ is also likely a worst-case (i.e., minimum surface brightness) scenario in the sense that there could be additional reionization sources at redshifts above $z \approx 7$, which would relax the requirements on those below. However, the dependence of the mean surface brightness required for reionization on the redshift interval is relatively weak, increasing by only 0.1, 0.4, and 0.8 mag as $\Delta z$ increases from 1 to 3, 1 to 10, and 1 to 30 (for $C \approx 1$).

3. OBSERVATIONS

We now compare the predictions of Paper I, summarized in the previous section, with recent observations from the UDF and GOODS. The UDF observations were made in 400 orbits on a single pointing with the wide-field channel of the Advanced Camera for Surveys. The two longest integrations, 144 orbits each, were made in the i band (F775W filter) and z band (F850LP filter). We base our analysis on the i-band dropouts ($z \approx 6$ galaxies) identified by Bunker et al. (2004) using the SExtractor program (Bertin & Arnouts 1996) in the final combined images. The magnitudes and colors of the objects were measured in apertures 0.5″ in diameter. The UDF catalog includes 53 objects with $i - z \geq 1.3$ and 22 with $i - z \geq 2.0$ down to a limiting magnitude of $z = 28.5$ at $S/N = 8$, where the incompleteness is only 2% (Table 1 of Bunker et al. 2004). We analyze the $i - z \geq 1.3$ and $i - z \geq 2.0$ subsamples separately. The latter may miss some high-redshift objects, but it should be nearly free of contamination by low-redshift objects. We have verified that the same selection criteria produce essentially the same samples of objects when applied to the $z$-detected catalog released by the UDF team (S. Beckwith et al. 2004, in preparation; M. Stiavelli et al. 2004, in preparation).

We combine these UDF observations with wider and shallower, but otherwise similar, observations from GOODS to obtain more reliable estimates of the bright part of the surface density–magnitude relation. For consistency with the UDF catalog, we again use magnitudes and colors measured in apertures 0.5″ in diameter, taken from the V1.0 GOODS catalog (Dickinson et al. 2004; M. Giavalisco et al. 2004, in preparation). This includes 77 objects with $i - z \geq 1.3$ and 14 with $i - z \geq 2.0$ down to a limiting magnitude of $z = 26.8$ at $S/N = 10$. We correct these counts for incompleteness, which increases from 10% at $z = 26.0$ to 40% at $z = 26.5$ for compact sources. We use the GOODS observations brighter than $z = 26.5$ and the UDF observations fainter than this magnitude. The expected uncertainties in the surface density because of Poisson fluctuations alone range from 60% at $z = 24$ to 20% at $z = 28$, while those due to large-scale structure range from 20% to 40% at the same magnitudes (Somerville et al. 2004; Bunker et al. 2004). We do not correct the observed mean surface brightness $\mathcal{H}$ and He, and the effect of recombinations (as described in detail in Paper I).

The minimum mean surface brightness of the reionization sources is given by $(f, C) = (1, 1)$; in this case, all Lyman continuum photons escape from the sources and on the clumpiness $C$ of the IGM, which in turn determines the recombination rate. The surface brightness required for reionization fixes the normalization of the curves in Figure 1, which are labeled by the corresponding parameters $(f, C)$. We have calculated these curves from the equation of ionization balance, including both H and He, and the effect of recombinations (as described in detail in Paper I).

The minimum mean surface brightness of the IGM, which in turn determines the recombination rate. The requirement that the sources be able to ionize all the hydrogen in the IGM corresponds, for a given spectral shape, to a definite mean surface brightness at any chosen wavelength ($\lambda_{\text{rest}} = 1400$ Å in all cases considered here). This surface brightness depends on the fraction $f$, of Lyman continuum photons that escape from the sources and on the clumpiness $C$ of the IGM, which in turn determines the recombination rate. The surface brightness required for reionization fixes the normalization of the curves in Figure 1, which are labeled by the corresponding parameters $(f, C)$. We have calculated these curves from the equation of ionization balance, including both H and He, and the effect of recombinations (as described in detail in Paper I).

The minimum mean surface brightness of the reionization sources is given by $(f, C) = (1, 1)$; in this case, all Lyman continuum photons escape from the sources and the recombination rate is minimum. For stellar sources, there is also a maximum mean surface brightness, given by the condition that they not produce too many heavy elements. We adopt the generous but non-rigorous limit $Z \leq 0.01 Z_\odot$ on the cosmic mean metallicity (the mean density of heavy elements in stars and interstellar and intergalactic matter divided by the mean baryon density) at $z = 6$ (explained in detail in Paper I). The shaded regions in Figure 1 are excluded by these constraints, while the clear regions are allowed.
for objects fainter than our detection limits in luminosity and/or surface brightness. In this sense, all our empirical estimates are lower limits to the true mean surface brightness.

Before comparing these observations with our predictions, we must examine the relation between the measured $z$-band magnitudes and the rest-frame 1400 Å magnitudes adopted in Figure 1. We estimate the offset between these magnitudes by convolving the total $z$-band response function with $10^5$ K and $5 \times 10^4$ K blackbody spectra truncated below rest frame 1216 Å and redshifted through the interval $5.8 < z < 6.7$. This procedure mimics observations of reionization sources composed of Population III and Population II stars with heavy H I absorption by some combination of stellar, interstellar, or intergalactic material. The resulting offsets between the $z$-band and rest-frame 1400 Å magnitudes are $-0.03$ mag for Population III sources and $+0.02$ mag for Population II sources. Such small offsets are the product of a fortuitous near-cancellation. Sources at $z \approx 5.8$ appear brighter in the $z$ band (by a few tenths of a magnitude) than at rest frame 1400 Å because their blue UV continua are measured at shorter wavelengths, which contributes a negative correction. However, objects at $z \approx 6.7$ appear fainter than at rest frame 1400 Å because the $z$ band samples mostly the part of the spectrum attenuated by H I, which contributes a positive correction. Thus, for a uniform distribution with exactly how much. The ionizing efficiency of a stellar population increases by a factor of 3 for a Salpeter IMF and a factor of 10 for a top-heavy IMF as the metallicity decreases from solar to zero metallicity (Schaerer 2003). The mean metallicity, averaged over all galaxies, is roughly solar in the present-day universe and must have been lower at the epoch of reionization, although we do not know by exactly how much. The ionizing efficiency of a stellar population also depends on the IMF, increasing by factors of 3 (for solar metallicity) to 10 (for zero metallicity) between a Salpeter IMF and a top-heavy IMF (Bruzual & Charlot 2003; Schaerer 2003). The latter is favored by recent theoretical studies of primordial star formation (e.g., Abel et al. 2000; Bromm et al. 2002).

The shortfall of ionizing photons estimated by Bunker et al. (2004) using the Madau et al. (1999) condition is at least a factor of 3. The different assumptions that we have made about the IGM temperature, stellar metallicity, and IMF each reduce the mean surface brightness required for reionization by factors of 2, 3–10, and 3–10, respectively. Any two of these factors would be enough to satisfy the reionization condition, and all three taken together (as we have assumed in Paper I) do so with a comfortable margin.

5. CONCLUSIONS

Our main conclusion is that the surface brightness–magnitude relation for $z \approx 6$ objects detected in the UDF and GOODS agrees remarkably well with our predicted relation for metal-poor reionization sources. In particular, the observed integrated surface brightness is consistent with that required for reionization with reasonable values of the escape fraction ($0.05 < f_e < 0.5$) and clumpiness parameter ($1 < C < 30$) if the sources are composed of either Population III or Population II stars with a top-heavy IMF. Reionization by sources with a Salpeter IMF, although possible, is more difficult, requiring both a high escape fraction and a very low metallicity.
We find that the shape of the observed surface brightness–magnitude relation at \( z \approx 6 \) is roughly similar to that of the Lyman break galaxies at \( z \approx 3 \) (consistent with the conclusions of Bouwens et al. 2004 and Bunker et al. 2004). However, we obtain somewhat better agreement if the luminosity function of the \( z \approx 6 \) galaxies has a brighter knee and a steeper slope.

It is worth noting that as the slope approaches the divergence value \( \alpha = 2 \), progressively more of the ionizing radiation comes from fainter, possibly undetected sources. Population II sources require higher values of \( f_c \) and lower values of \( C \) than Population III sources, because cooler stars are less efficient ionizers. It is not clear, however, whether sufficiently high values of \( f_c \) could be reached in sources that were already enriched in metals and dust and therefore likely to have more UV absorption.

The predictions presented here are based on the assumption that reionization occurs over the relatively small interval of redshift \( \Delta z \approx 1 \) just above \( z \approx 6 \). It is remarkable that even in this most demanding case, the observed objects are sufficient to reionize the IGM. Of course, it is possible that reionization began much earlier. The polarization of the CMB measured by WMAP indicates that the IGM was at least partly ionized at \( z \sim 20 \) (albeit with large uncertainties; Spergel et al. 2003). However, the high temperature of the IGM at \( z \approx 4 \) inferred from quasar absorption-line systems indicates that much of the heating accompanying reionization occurred at \( z \ll 20 \) (Theuns et al. 2002; Hui & Haiman 2003). Some theoretical models suggest that reionization might have occurred more than once, for example, at \( z \approx 15 \) and then again at \( z \approx 6 \) (Cen 2003). We conclude that even if the \( z \approx 6 \) objects observed in the UDF and GOODS were not the only sources responsible for the reionization of the IGM, they would have contributed substantially to its final stages.

An important future development will be to extend this analysis to observations at infrared wavelengths. In this way, we could attempt to detect additional reionization sources at redshifts beyond \( z \approx 7 \) and to determine their contribution relative to the sources at lower redshift discussed here. Such observations in and near the UDF have already been made with the Near-Infrared Camera and Multi-Object Spectrometer on HST and will become available soon (R. Thompson et al. 2004, in preparation). Further progress could be made with the Wide Field Camera 3 if and when it is installed on HST. However, a complete census of all the reionization sources, especially any at \( z \gtrsim 12 \), must await the launch of JWST.

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