DEEP VERY LARGE TELESCOPE \(V\)-BAND IMAGING OF THE FIELD OF A \(z = 10\) CANIDATE GALAXY: BELOW THE LYMAN LIMIT?\(^1\)

M. D. LEHNERT and N. M. FÖRSTER SCHREIBER

Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse, 85748 Garching bei München, Germany

AND

M. N. BREMER

Department of Physics, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, UK

Received 2004 November 11; accepted 2004 December 16

ABSTRACT

We present a deep 16.8 ks \(V\)-band image of the field of a candidate \(z = 10\) galaxy magnified by the foreground (\(z = 0.25\)) cluster A1835. The image was obtained with FORS1 on VLT-Kueyen to test whether the \(V\) band lies below the Lyman limit for this very high redshift candidate. A detection would unambiguously rule out that the source is at \(z = 10\). The 3 \(\sigma\) detection limit of the image in the area of the \(z = 10\) candidate is \(V_{\text{AB}} = 28.0\) mag in a 2\,\textprime\ diameter aperture (about 3 times the seeing FWHM of 0\,\textprime.7). No source at the position of the candidate galaxy is detected down to this limit. Formally, this is consistent with the \(V\)-band probing below the Lyman limit in the rest frame of a \(z = 10\) source. However, given the recent nondetection of the object in a deep \(H\)-band exposure with NIRI on Gemini North down to \(H_{\text{AB}} = 26.0\) mag (3 \(\sigma\) in a 1.4\,\textprime\ aperture) and concerns about the detection of the reported associated emission line, it may be possible that this source is spurious. We discuss several astrophysical possibilities to explain the puzzling nature of this source and find none of them compelling.

Subject headings: cosmology: observations — early universe — galaxies: distances and redshifts — galaxies: evolution — galaxies: formation

1. INTRODUCTION

Motivated by the discovery of high-redshift, \(z \approx 6\) quasars with what appeared to be Gunn-Peterson troughs (Becker et al. 2001; Djorgovski et al. 2001), many research groups began to search for the sources responsible for reionization (see, e.g., Lehnert & Bremer 2003; Bremer et al. 2004b; Stanway et al. 2004a, 2004b; Bunker et al. 2003; Ajiki et al. 2003; Rhoads et al. 2003; Bouwens et al. 2004; Hu et al. 2004). The Wilkinson Microwave Anisotropy Probe (\(WMAP\)) result of the surprising detection of a large Thompson electron optical depth of \(\tau = 0.17 \pm 0.04\) (Kogut et al. 2003) and questions about whether the intergalactic opacity at \(z \approx 6\) is due to the neutral intergalactic medium (IGM) or to discrete absorbers (e.g., Songaila & Cowie 2002) have led observers to try and push discovery techniques into the near-infrared (NIR) and beyond the redshift of the most distant Sloan quasars (Pello et al. 2004; Kneib et al. 2004).

To reconcile the possible Gunn-Peterson troughs observed in high-redshift quasar spectra and the \(WMAP\) results, the fact that the ionizing photon density at high redshift appears to be declining (e.g., Lehnert & Bremer 2003; Bunker et al. 2003) and the rapidly increasing density necessary to ionize the IGM at successively higher redshifts (e.g., Madau et al. 1999) suggest that the universe may have had a complex reionization history. Indeed, these arguments led some researchers to propose complex models such as extended partial reionization (e.g., Madau et al. 2004; Ricotti & Ostriker 2004) or twice reionization (e.g., Cen 2003; Ciardi et al. 2003; Wyithe & Loeb 2003). In these complex scenarios, the discovery of even one high-redshift star-forming galaxy provides powerful constraints on the sources of reionization and on how star formation proceeded in the early universe (e.g., Ricotti et al. 2004).

But discovering galaxies at redshifts beyond \(z \approx 6\) becomes increasingly challenging. Rest-frame emission longward of the Lyman limit is redshifted to observed \(\lambda > 7500\) \AA, and the faintness of the galaxies makes them extremely difficult to detect. The essential spectroscopic confirmation is hampered by the dramatic increase in the density of telluric OH emission bands at \(\lambda > 7500\) \AA. There are regions 100–200 \AA\ wide that are relatively devoid of OH lines. Narrowband surveys for high-redshift sources using filters with central wavelengths that lie within these windows have been successful (e.g., Hu et al. 2004). Outside of these windows, even determining redshifts of color-selected galaxies is generally very difficult at \(z \approx 6\).

One technique developed to overcome the difficulty of detecting the most distant galaxies takes advantage of gravitational lensing by an intervening galaxy cluster to boost the apparent brightness of background sources. This boost can be as much as a factor of 10–100 along the critical lines for lensing. Santos et al. (2004) proved the feasibility of this technique out to \(z = 5.6\), and Kneib et al. (2004) discovered a probable lensed \(z \sim 7\) Lyman break galaxy behind A2218. The efficiency of gravitational lensing assisted searches compared to blank-field searches is, however, sensitive to the slope of the luminosity function, and thus its overall utility in finding large numbers of high-redshift galaxies has yet to be assessed.

Pelló et al. (2004) reported the identification of a highly magnified galaxy lying on a critical line of the \(z = 0.25\) cluster A1835 (which they denoted A1835-1916). Their data set included broadband optical imaging from the \(Hubble\) \(Space\) \(Telescope\) (\(HST\)) and the Canada-France-Hawaii Telescope (CFHT) along with NIR imaging and spectroscopy with ISAAC at the VLT. The object was undetected in the \(V, R, I\) optical bands and only detected at 4 \(\sigma\) in \(H\) and 3 \(\sigma\) in \(K\). The \(J\)-band detection quoted by

\(^1\) Based on Director’s Discretionary Time observations collected at ESO VLT under program 273.A-5028(A).
Pelló et al. (2004) is formally an upper limit. The optical non-detection, the large break between the J and H bands, and the blue $H - K_s$ color ($H_{AB} - K_{s,AB} < 0$) found by Pelló et al. could possibly indicate a young galaxy at extremely high redshift. In their J-band spectroscopy Pelló et al. reported an emission line at 1.33745 μm, detected in two separate wavelength settings of the spectograph and with a combined significance of 4–8 $\sigma$. The photometry, together with the lensing model suggesting the source lies on a caustic for very high redshift (with a magnification factor between 25 and 100 as being most likely), led Pelló et al. to argue that the line is most likely Lyα at $z = 10.0175$. Unfortunately, the signal-to-noise ratio (S/N) of the spectrum is insufficient to show the telltale signature of the line profile asymmetry of highly redshifted Lyα to rule out other line identifications. Given the uncertainties in the lensing model, the most important piece of evidence upon which the conclusion of $z = 10$ rests is the shape of the spectral energy distribution (SED) measured from the imaging data.

However, the high-redshift nature of this source has been recently questioned. Based on new independent H-band data obtained with NIRI at the Gemini North telescope, Bremer et al. (2004a) did not detect the $z = 10$ candidate down to the 3 $\sigma$ limit of $H_{AB} = 26.0$ mag. This limit is 1 magnitude deeper than the 4 $\sigma$ detection quoted by Pelló et al. (2004) in their ISAAC data. This significantly weakens the main evidence for a redshift of 10, which relies on the strength of the break between the optical and J bands and the H band. The photometry no longer constrains the redshift, and other identifications for the emission line from a lower redshift source remain possible.

Before the Bremer et al. (2004a) results were obtained, we were awarded Director’s Discretionary Time with FORS1 at the VLT to conduct V-band imaging of the field around the $z = 10$ candidate and push the sensitivity to fainter levels than presented by Pelló et al. (2004). A V-band detection would be decisive: it would demonstrate beyond any doubt that the source is not at $z = 10$. Besides probing rest-frame wavelengths around 500 Å for $z = 10$, well below the Lyman limit, we chose the V band to reach, within a reasonable observing time, very sensitive limits compared to other optical or NIR bands and thus provide the best chance of detecting a reddened $z = 1–2$ object, which seems a likely alternative (see Bremer et al. 2004a).

2. DATA AND ANALYSIS

2.1. Observations and Data Reduction

The V-band observations of A1835 were carried out during Director’s Discretionary Time on the nights of 2004 July 9, 16, and 19 (UT). We used FORS1 on the VLT-Kueyen telescope in imaging mode with a projected scale of 0″200 pixel−1. We took 48 separate frames of 350 s each, for a total integration time of 16.8 ks. Half of the integration time was taken on 2004 July 16 (2004a) did not detect the Hα measured from the imaging data. The photometry together with the lensing model suggesting the source lies on a caustic for very high redshift (with a magnification factor between 25 and 100 as being most likely), led Pelló et al. (2004) is formally an upper limit. The signal-to-noise ratio (S/N) of the spectrum is insufficient to show the telltale signature of the line profile asymmetry of highly redshifted Lyα to rule out other line identifications. Given the uncertainties in the lensing model, the most important piece of evidence upon which the conclusion of $z = 10$ rests is the shape of the spectral energy distribution (SED) measured from the imaging data.

However, the high-redshift nature of this source has been recently questioned. Based on new independent H-band data obtained with NIRI at the Gemini North telescope, Bremer et al. (2004a) did not detect the $z = 10$ candidate down to the 3 $\sigma$ limit of $H_{AB} = 26.0$ mag. This limit is 1 magnitude deeper than the 4 $\sigma$ detection quoted by Pelló et al. (2004) in their ISAAC data. This significantly weakens the main evidence for a redshift of 10, which relies on the strength of the break between the optical and J bands and the H band. The photometry no longer constrains the redshift, and other identifications for the emission line from a lower redshift source remain possible.

Before the Bremer et al. (2004a) results were obtained, we were awarded Director’s Discretionary Time with FORS1 at the VLT to conduct V-band imaging of the field around the $z = 10$ candidate and push the sensitivity to fainter levels than presented by Pelló et al. (2004). A V-band detection would be decisive: it would demonstrate beyond any doubt that the source is not at $z = 10$. Besides probing rest-frame wavelengths around 500 Å for $z = 10$, well below the Lyman limit, we chose the V band to reach, within a reasonable observing time, very sensitive limits compared to other optical or NIR bands and thus provide the best chance of detecting a reddened $z = 1–2$ object, which seems a likely alternative (see Bremer et al. 2004a).

2.2. Photometry

Figure 1 shows the 20″ × 20″ region in our V-band image around the reported location of the candidate $z = 10$ galaxy. We do not detect any source at this position down to the faintest levels reached in our data. This implies a 3 $\sigma$ limit of $V_{AB} > 28.0$ mag in a 2″ diameter aperture, as described below. Our limit is 0.6 mag deeper than the 3 $\sigma$ limit of Pelló et al. (2004) given for a 0″6 aperture, or about 3.5 mag deeper for an aperture of 3 times the FWHM (0″76) of their V-band data, assuming uncorrelated Gaussian noise.

We assessed our ability to reliably set a meaningful upper limit to any possible source at the position of the $z = 10$ candidate using three different techniques. First we established the pixel-to-pixel rms variations in the background across the entire image. For this purpose, we used the SExtractor software (Bertin & Arnouts 1996). SExtractor estimates the local background level in a mesh grid over the image. These local background estimates are iteratively clipped until they converge to ±3 $\sigma$ around the median of all meshes. The histogram of all remaining unclipped pixels is then used to determine the rms variations of the background noise in the image. This procedure yielded an overall 3 $\sigma$ detection limit of $V_{AB} = 27.6$ mag in a 2″ diameter aperture. However, this limit is pessimistic, because our image is very crowded with cluster and background galaxies at the depths reached: the surface density of faint sources is such that there is typically only about 4″ between adjacent point sources, for which the S/N is optimized with an aperture of 1.5 times the FWHM.

2 The weight $w$ is applied as the multiplicative factor $w^{-2}$.
3 The ESO FORS1 zero points are available at http://www.eso.org.
4 We refer to the Vega photometric system when not explicitly indicating AB magnitudes. For the V band, the AB correction is very small, with $V_{AB} - V_{Vega} = 0.014$ mag for FORS1 accounting for the full system transmission.
5 This aperture size corresponds to 3 times the seeing FWHM in the combined data and has a negligible aperture correction except for the brightest point sources and the most extended objects. We note that it leads to conservative limits for faint point sources, for which the S/N is optimized with an aperture of 1.5 times the FWHM.
Bject and is 2/C6z the area around the reflect extended light profiles of the myriad of galaxies in the magnitudes, 27.6, 27.8, and 28.0 mag, within cally dependent on the number of apertures or their exact place- and positions to ensure that our final estimates were not criti- tions of/C27V limit of 0060 apertures 2ported location of the sources down to the position of the ber of point sources that can be placed nonredundantly close to sources in this region. The high degree of crowding limits the num- robust methods, we adopted between the measured and true input brightness was expected for a 3/C27V ¼ 7. The circle indicates the location of the candidate ob- ject, we focused our analysis to 10 candidate to about 20. We recovered the sources down to VAB ¼ 28.0 mag as the detection limit of VAB ¼ 27.8 mag.

To further determine the robustness of our detection limits, we placed 20 artificial point sources each at three different AB magnitudes, 27.6, 27.8, and 28.0 mag, within ±20′′ of the reported location of the z ¼ 10 candidate and avoiding all obvious sources in this region. The high degree of crowding limits the number of point sources that can be placed nonredundantly close to the position of the z ¼ 10 candidate to about 20. We recovered the sources down to VAB ¼ 28.0 mag at a rate similar to that expected for a 3 σ detection limit (i.e., 50%), and the dispersion between the measured and true input brightness was ±0.3–0.4 mag. Given the excellent agreement between the two most robust methods, we adopted VAB ¼ 28.0 mag as the detection limit in a 2″ aperture at the position of the z ¼ 10 candidate.

3. DISCUSSION

The nondetection in our VLT FORS1 V-band data down to a faint limit has implications for the nature of the source investigated by Pelló et al. (2004). Formally, a nondetection is consistent with the candidate having a redshift of 10. The Bessel V-band filter has an effective wavelength of 5540 Å and half- maximum transmission at about 5000 and 6000 Å. For z ¼ 10, these wavelengths correspond to 500 Å and the range ~450–550 Å in the rest frame—well below the Lyman limit and completely opaque. The lower limit to the redshift, if the V-band nondetection is caused solely by the IGM opacity below the Lyman limit, is ~5.6. However, there is substantial opacity within the Lyman forest at these redshifts, and thus V-band Lyman break or drop-out galaxies have redshifts that are usually less than this (see, e.g., Bremer et al. 2004b).

Although our V-band nondetection may allow for z ≥ 5.6 or even z ¼ 10, this is not the only interpretation possible in view of other lines of evidence that have recently come to light. There are certainly two other hypotheses that are equally plausible and perhaps significantly more likely.

The strongest evidence for the z ¼ 10 interpretation presented by Pelló et al. (2004) relied on the large break among the optical, J, and H bands and the subsequent detection of an emission line at 1.33745 μm. However, this evidence has now been called into question. Bremer et al. (2004a) did not detect the candidate object in their new independent and 1 mag deeper H-band image from NIRI down to HAB ¼ 26.0 (3 σ). This greatly weakens the argument based on the break strength (as well as the blue H – Kσ color) that supported the claim for the emission line being Lyα at z ≈ 10. Furthermore, Weatherley et al. (2004) have recently questioned the robustness of the line detection. However, this was based on a reanalysis of the spectrosocopic data used by Pelló et al. (2004), and subtle differences in reduction techniques could lead to contentious results. It is probably reasonable to conclude that the significance of the line is difficult to judge.

If the object is not at a redshift of 10, then what could it be? One way forward is to assume the reality of the line, use the sensitive H-band limit of Bremer et al. (2004a), and assume an alternative line identification to determine whether the emission properties are reasonable for a galaxy at a lower redshift. Bremer et al. (2004a) argued that the source could be a dwarf/H II galaxy at intermediate redshift and that lines such as the [O II] λλ3726, 3729 doublet, [O II] λ5007, or Hα at 1.0 < z < 2.6 are the most likely alternatives to Lyα. If it were [O III], then the line width and luminosity would be consistent with the local relationship for dwarf/H II galaxies between these quantities (e.g., Melnick et al. 2000). In light of our new V-band results, we wish to further this argument.

Assuming the line is [O III] at z ¼ 1.67 and adopting reasonable cosmological parameters (H0 ¼ 70 km s−1 Mpc−1, Ωm ¼ 0.3, and Ωλ ¼ 0.7), our V-band limit implies an unlensed absolute magnitude fainter than −16.4 mag at 2080 Å. Since there is no published detailed analysis of the mass model of the intervening cluster, it is difficult to quantitatively assess the magnification factor for z ¼ 1.67 (Pelló et al. suggested a magnification factor of between 25 and 100 for a source at z ¼ 10). Conservatively, we assume no lensing; lensing will only make the source intrinsically fainter. The comoving density of galaxies in the local universe with absolute magnitude −16.5 at 2000 Å is 3/02000 ≈ 10−15 Mpc−3 mag−1 (Treyer et al. 1998). The number of such sources on the sky with 1.45 < z < 1.95 is then ~50 arcmin−2 if the UV luminosity function does not evolve out to z ¼ 1.7. The luminosity function of z ≈ 3 Lyman break galaxies implies a roughly similar surface density for such faint objects (Steidel et al. 1999). Comparable densities would be inferred to a factor of ~1.5 if the line were Hα at z ¼ 1.04 or [O III] at z ¼ 2.59.
The surface density of sources down to the detection limit of our image is $>$50 arcmin$^{-2}$ (modulo the incompleteness). Therefore, the probability of finding and perhaps even mistaking it for a very high redshift source is consequently high. The immediate explanation is that the source might simply be fainter. However, this poses problems when trying to reconcile the broadband flux limits with the reported emission-line flux.

The 3 $\sigma$ $V$-band limit obtained by Bremer et al. (2004a) coupled with the line flux given by Pello et al. (2004) implies an observed equivalent width (EW) of $W_{\text{obs}} > 170$ Å (assuming a flat $f_{\text{c}}$ spectrum; Sullivan et al. 2000). For sources at $z \approx 1.7$, this implies observed $V_{\text{AB}} - H_{\text{AB}} \leq 0$. Supposing again that the source is at $z = 1.67$ and assuming conservatively that it has a flat $f_{\text{c}}$ spectrum, our limit of $W_{\text{rest}} > 28.0$ mag implies an $H$-band limit of $H_{\text{AB}} > 28.0$ mag and, repeating the reasoning above, a rest-frame EW for [O iii] of $W_{\text{rest}} > 400$ Å ($\geq 500$ Å if $H_{\alpha}$, $\geq 300$ Å if [O ii]). For a bluer spectrum, as observed locally, the line EW limit only increases. A similar argument would apply to any other optical line. Such high EWs are rarely observed and would require a very young age ($< 10$ Myr) and perhaps an initial mass function heavily skewed toward massive stars.

Summarizing the above arguments, our sensitive $V$-band limit implies a faint intrinsic UV ($\sim 2000$ Å) absolute magnitude. Plausible luminosity functions predict a high surface density of such objects and thus a high probability of detection if the source were just bright enough to match the 3 $\sigma$ limiting magnitude of our $V$-band image. No object is detected at the expected location despite the high-density $\geq 50$ arcmin$^{-2}$ of 3 $\sigma$ sources in the data. Postulating then that the object could be fainter, the lower limits on the rest-frame EW of the emission line become very large, and the probability of detecting such a source becomes very low. Thus, in view of the simple astrophysics of line emission, the scenario of an intermediate redshift dwarf does not appear very likely given the difficulties in reconciling the broadband limits with the emission-line flux. In addition, although largely circumstantial, the arguments could perhaps cast doubt on the reported line flux (Weatherley et al. 2004).

The other possible scenario is that the source may be transient or variable. The NIR ISAAC images and spectra presented by Pello et al. (2004) were taken in 2003 February and late June to early July, respectively. The NIRI $H$-band data were collected during two nights in 2004 in late May and early June. The $I$-band data discussed here were obtained in 2004 in mid-July. Overall, these observations span a period of about a year and a half.

Given the ecliptic latitude of the A1835 field at about 14°, one hypothesis could be that the source is a solar system object with a large proper motion. The tightest constraint comes from the time over which all of the Pello et al. (2004) ISAAC $H$-band data were taken. The observations were carried out over 24 hr on 2003 February 15 and 16, and the seeing in the final $H$-band image is $\sim 0.5$ s. Conservatively, for the source not to appear extended would imply an angular velocity of $< 0.5/(24 \text{ hr})$ or $< 0.02 \text{ hr}^{-1}$. If the source is bound to the Sun and consistent with a distant object like Pluto, for example, with a tangential velocity of 5 km s$^{-1}$, it would lie at more than $D = 1240$ AU. To be unresolved in the $0.5$ $H$-band image at the distance derived from the proper motion limit, the source would have to be smaller than $\sim 10$ Jupiter diameters. The brightness of an object illuminated by reflected sunlight and assuming an albedo of one is related to its angular diameter, $\theta$, by $m = m_0 - 2.5 \log (\theta/2D)$. From the size calculated above, the source would have $H \approx 55$ mag. An object with the magnitude as claimed by Pello et al. (2004) would have to be a million times larger than what we roughly estimated and thus would violate the size constraint by 6 orders of magnitude. It is possible to relax these constraints by an order of magnitude, but even given more optimistic estimates, a solar system object seems highly unlikely.

It is more difficult to estimate the probability that the source is a high-redshift supernova, $\gamma$-ray burst, or perhaps something more exotic (e.g., Stern et al. 2004 and references therein). Dahlen et al. (2004) determined a supernova (SN) rate of about $5.5 \times 10^{-4}$ SN yr$^{-1}$ Mpc$^{-3}$ at $z \approx 0.7$--0.8 and using a model for the star formation rate density evolution, they estimate about a factor of 2 increase in the SN rate at $z = 2$. The magnitude at which Pello et al. (2004) claim to have detected the source is $H_{\text{AB}} = 25.0$. It is difficult to know what the redshift of the source might be, especially since the photometry for a transient provides no constraints on the redshift. It is worth noting that distant SNe generally have optical magnitudes fainter than the Pello et al. detection (e.g., Stolger et al. 2004; Dahlen et al. 2004), and given the relatively blue SED of SNe this means that the $z = 10$ candidate would have been one of the brighter SNe (it is of course magnified by an unknown amount, which could account for its relative brightness). At any rate, we can estimate the chances of finding a SN serendipitously in their field. Assuming that the SN was caught within 30 days of its peak, that the redshift range of the SN was 0.5--1.0 (roughly consistent with the range in Dahlen et al. 2004), and that the area in the detection image was 6 arcmin$^2$, we would have expected 0.22 SN in the field based on the Dahlen et al. (2004) SN rate density. Thus, the candidate as an intermediate-redshift SN cannot be ruled out. However, this is surely optimistic given the magnitude of the detection claimed in the Pello et al. $H$-band image and the unknown magnification. Lensing would decrease the probability by decreasing the effective area sampled. Requiring the SN to be observed more closely to its peak in order to make detection more likely would (linearly) lower the relative probability of observing it.

Neither of the transient hypotheses can explain the line detection. One would have to postulate that it comes from the host galaxy in the case of a SN, from which there has been no subsequent continuum detection. Given the EW arguments we made previously, this would have to be a very unusual object to escape detection. For a solar system object, the gap between the dates of the imaging and spectroscopy means that the source would have moved a significant distance from the discovery position and not within the subsequent slit spectroscopy. Therefore, none of the possible transient hypotheses explain simply or logically all of the claims in Pello et al. (2004). Given the $H$-band nondetection of the source down to faint limits by Bremer et al. (2004a) and now in the $V$ band and the unlikely nature of any galaxy with the properties (lower limits) observed, it is tempting to conclude that the most likely explanation is that the source is spurious.
We would like to thank the referee, Pat McCarthy, for his comments and Roser Pello and Daniel Schaerer for their arguments and insights. We wish to thank the ESO Director General, Catherine Cesarsky, for the generous allocation of observing time and Bruno Leibundgut for his curiosity and support. We are grateful to the ESO USG, DMD, and Paranal staff for conducting these observations and to Mario van den Ancker and Roberto Mignani, in particular, for their dedication and effort.

REFERENCES

Ajiki, M., et al. 2003, AJ, 126, 2091
Becker, R. H., et al. 2001, AJ, 122, 2850
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Bouwens, R. J., et al. 2004, ApJ, 606, L25
Bremer, M. N., Jensen, J., Lehnert, M. D., Förster Schreiber, N., & Douglas, L. 2004a, ApJ, 615, L1
Bremer, M. N., Lehnert, M. D., Waddington, I., Hardcastle, M. J., Boyce, P. J., & Philipps, S. 2004b, MNRAS, 347, 7
Bunker, A. J., Stanway, E. R., Ellis, R. S., McMahon, R. G., & McCarthy, P. J. 2003, MNRAS, 342, 47
Cen, R. 2003, ApJ, 591, 12
Ciardi, B., Ferrara, A., & White, S. D. M. 2003, MNRAS, 344, L7
Dahlen, T., et al. 2004, ApJ, 613, 189
Djorgovski, S. G., Castro, S., Stern, D., & Mahabal, A. A. 2001, ApJ, 560, L5
Hu, E. M., Cowie, L. L., Capak, P., McMahon, R. G., Hayashino, T., & Komiyama, Y. 2004, AJ, 127, 563
Kneib, J.-P., Ellis, R. S., Santos, M. R., & Richard, J. 2004, ApJ, 607, 697
Kogut, A., et al. 2003, ApJS, 148, 161
Lehnert, M. D., & Bremer, M. N. 2003, ApJ, 593, 630
Madau, P., Haardt, F., & Rees, M. J. 1999, ApJ, 514, 648
Madau, P., Rees, M. J., Volonteri, M., Haardt, F., & Oh, S. P. 2004, ApJ, 604, 484
Melnick, J., Terlevich, R., & Terlevich, E. 2000, MNRAS, 311, 629
Pelló, R., Schaerer, D., Richard, J., Le Borgne, J.-F., & Kneib, J.-P. 2004, A&A, 416, 35
Rhoads, J. E., et al. 2003, AJ, 125, 1006
Ricotti, M., Hachnelt, M. G., Pettini, M., & Rees, M. J. 2004, MNRAS, 352, L21
Ricotti, M., & Ostriker, J. P. 2004, MNRAS, 350, 539
Santos, M. R., Ellis, R. S., Kneib, J.-P., Richard, J., & Kuijken, K. 2004, ApJ, 606, 683
Songaila, A., & Cowie, L. L. 2002, AJ, 123, 2183
Stanway, E. R., Bunker, A. J., McMahon, R. G., Ellis, R. S., Treu, T., & McCarthy, P. J. 2004a, ApJ, 607, 704
Stanway, E. R., et al. 2004b, ApJ, 604, L13
Steidel, C. C., Adelberger, K. L., Giavalisco, M., Dickinson, M., & Pettini, M. 1999, ApJ, 519, 1
Stern, D., et al. 2004, ApJ, 612, 690
Stolger, L.-G., et al. 2004, ApJ, 613, 200
Sullivan, M., Treyer, M. A., Ellis, R. S., Bridges, T. J., Milliard, B., & Donas, J. 2000, MNRAS, 312, 442
Treyer, M. A., Ellis, R. S., Milliard, B., Donas, J., & Bridges, T. J. 1998, MNRAS, 300, 303
Weatherley, S. J., Warren, S. J., & Babbedge, T. S. R. 2004, A&A, 428, L29
Wyithe, J. S. B., & Loeb, A. 2003, ApJ, 588, L69