HIGH REDSHIFT GALAXIES AND THE SOURCES OF REIONIZATION

MATTHEW D. LEHNERT[1] AND MALCOLM BREMER[2]

[1]MAX-PLANCK-INSTITUT FUER EXTRATERRESTRISCHE PHYSIK,GARCHING BEI MUENCHEN, GERMANY
[2]DEPARTMENT OF PHYSICS, UNIVERSITY OF BRISTOL, U.K.

TWO OF THE MOST IMPORTANT ISSUES IN MODERN ASTROPHYSICS, WHAT REIONIZED THE HYDROGEN IN THE UNIVERSE, AND HOW THE FIRST OBJECTS FORMED, HAVE BEEN ADDRESSED BY A SERIES OF VLT OBSERVATIONS. THEY INDICATE THAT THE HYDROGEN WAS REIONIZED BY ULTRA VIOLET PHOTONS FROM STARS AND NOT ACTIVE GALACTIC NUCLEI, WITH MOST OF THE PHOTONS ARISING IN RELATIVELY FAINT LOW MASS GALAXIES.

THE UNIVERSE HAS BEEN expanding and cooling ever since the Big Bang. Several seconds after the Big Bang, baryons (mainly protons, hydrogen nuclei) and leptons (mainly electrons) had formed. At this point the Universe was far too hot for the electrons to become bound to the protons. Three hundred thousand years later, the temperature of the Universe had dropped to below a few thousand degrees Kelvin allowing the electrons and protons to combine, forming neutral hydrogen. For up to a billion years thereafter, the vast majority of the hydrogen, itself the dominant form of baryonic matter, remained in this neutral state.

The hydrogen that pervades intergalactic space in the current-day Universe is again completely ionized. At some point around a billion years after the Big Bang, the hydrogen in the Universe was reionized. The gas is now kept ionized by the integrated ultraviolet photon background. Ultra-violet photons with energies above 13.6 eV (wavelengths shorter than 91.2 nm) have sufficient energy to ionize the hydrogen atoms when they interact, unbinding the electrons from the protons. The majority of these photons in the current-day Universe are emitted by Active Galactic Nuclei, particularly quasars, emitted as material falls into the supermassive black holes at their centres.

The amount of UV photons emitted by known quasars has been sufficient to ionize the intergalactic hydrogen for most of the history of the Universe. However, at high redshifts (above z=4, up to when the Universe was about 10 per cent of its current age) it was not clear until recently whether quasars and other AGN produced the bulk of the ionizing photons.

The reason for this uncertainty was threefold. Firstly, it has been known for some time (e.g., Schmidt, Schneider, & Gunn 1995; Fan et al. 2001) that luminous quasars were far rarer earlier on in the history of the Universe than when it was about half its current age. Unless the relative numbers of luminous and less luminous AGN favoured the low-luminosity AGN at high redshifts, the ionizing photon density from these objects was lower earlier on in the Universe. Secondly, the Universe was smaller, and so denser, and consequently it was harder to keep the hydrogen ionized. Thirdly, it is known that there is far less star formation in the Universe today than earlier on in its history, so it is entirely possible that at some earlier time the majority of UV photons were emitted by hot young stars in star forming regions in galaxies. This possibility is particularly interesting as it links the formation of the first generations of stars and galaxies to the changing ionization state of most of the baryonic matter in the Universe.

In order to understand whether UV photons from stars or AGN initiated the reionization of the Universe, the epoch of reionization needed to be determined and then the relative impact of AGN and star-forming galaxies on the ionizing photon budget at that epoch needed to be determined.

In the late 1960s it was realised that the epoch of reionization would be revealed in the optical spectra of sufficiently distant quasars. Scheuer (1965) and Gunn and Peterson (1965) realised that a "trough" would be seen in their redshifted UV spectra, caused by the UV photons being absorbed by the neutral hydrogen at redshifts corresponding to the time before reionization. This trough would be produced even if only one per cent of the hydrogen was neutral, so strictly the edge of the trough marked the end of reionization; the process could have started considerably earlier. Identification of this trough awaited the discovery of at least one quasar seen at a redshift prior to that of reionization. Only in 2001 was the Gunn-Peterson trough finally discovered (Becker et al., 2001, Fan et al., 2001) in the spectra of SDSS quasars at z>6. These results implied that the end of reionization occurred at z=5.7–6, just under a billion years after the Big Bang. Measurements of the polarization of the Cosmic Microwave Background by the WMAP satellite (Kogut et al. 2003) seem to indicate a higher redshift for 50 per cent reionization, consistent with reionization occurring over a few hundred million years.

FINDING THE SOURCES THAT CONTRIBUTED TO THE "END OF RE-IONIZATION"

This result left open the question of the origin of the UV photons which reionized the hydrogen. We realised that we might be able to address this issue with VLT observations of deep fields using FORS2. The large VLT aperture combined with the excellent red sensitivity of the recently-upgraded FORS2 CCD arrays meant that it was now feasible to carry out deep ground-based imaging and spectroscopy in order to detect faint quasars and galaxies at $z > 5$ which may emit the ionizing photons.

In order to determine the feasibility of these observations, we used simulations to determine the expected colours of quasars and galaxies at high redshifts. Both quasars and star-forming galaxies have intrinsically flat rest-frame UV spectra which can be reddened by surrounding gas and dust. Dusty objects would count little towards the ambient UV photon budget, and so were ignored. Genuinely high redshift objects could be identified by sharp breaks in their spectra due to strong absorption of the UV photons

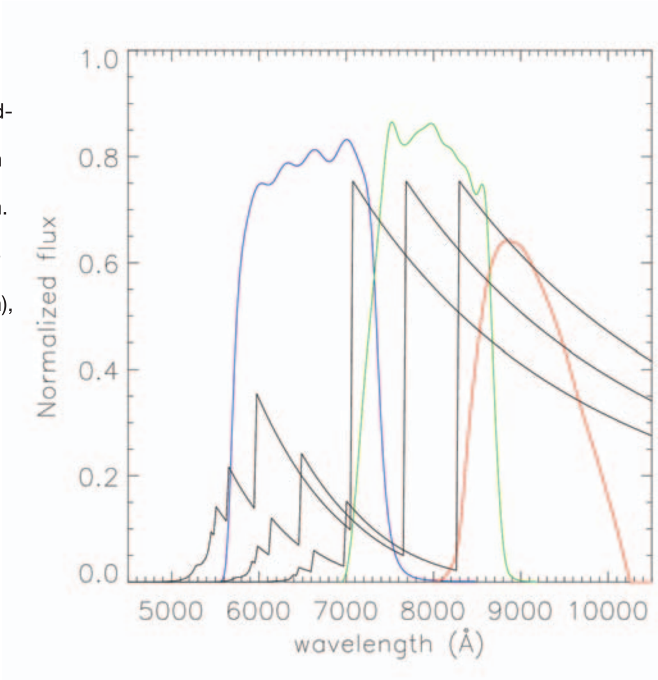


Figure 1: Power-law spectral energy distributions shown for three redshifts (4.8,5.3, and 5.8) and including absorption due to the intergalactic medium below 121.5 nm. The three colour curves represent the filter transmission of the *R* filter (in blue), the *I* filter (in green), and the *z*-band filter (in red) including the response of the CCD array.

by intervening hydrogen gas. Multi-colour imaging would identify these sources as they would "disappear" in images taken through filters sensitive to light with wavelengths shorter than that of the break (Fig. 1). This "Lyman break" technique for identifying distant galaxies has been in use for over a decade and has been championed by Steidel and collaborators to find $z = 3$ and 4 galaxies. Whereas those galaxies show sharp breaks in their spectra at wavelengths up to 500 nm, we needed to look for objects with breaks longward of about 650 nm in order to discover sources at $z > 5$.

We soon realised we had two main options. We could search for "*R*-band dropouts", objects which displayed a break between the *R* and *I* bands (allowing us to identify objects with $4.8 < z < 5.8$ with a median redshift of 5.3, according to our simulations), or "*I*-band dropouts" (objects potentially at $z > 5.5$). We chose to search for the former for several practical reasons.

Firstly, to identify a break between the *R* and *I* bands is easier and requires less telescope time than between the *I* and *Z* bands (required to identify *I*-band dropouts) because FORS2 is more sensitive in *R* and *I* than in *Z*. Secondly, contamination of our sample of candidates with lower redshift objects and stars would be far easier to identify (Fig. 2). Imaging in *R,I* and *Z* we could identify intrinsically flat spectrum sources with clear breaks between *R* and *I* fairly straightforwardly, but with only a detection in *Z* it would be unclear whether our sources were intrinsically flat spectrum with a break, or were intrinsically red sources, like low mass stars, sub-stellar objects and lower redshift reddened galaxies. Thirdly, we did not know how the luminosity function would evolve. Because of the increasing distance modulus and increased absorption by intervening hydrogen, a galaxy at $z = 6$ would be detected at far worse signal-to-noise in the *Z*-band than a similarly luminous galaxy at $z = 5.3$ in the same exposure time. Unless the luminosity function was unusually flat, our images may not have sampled enough volume to detect many I-band dropouts. Given that only 150 million years of cosmic time passes between $z = 6$ and $z = 5.3$ we took the view that the luminosity function of high redshift sources could not change dramatically over that time and so we could concentrate on the easier-to-observe *R*-band dropouts.

We identified a field of about 200 arcmin^2 with extremely low galactic extinction and infrared cirrus emission that was well-placed in RA for ease of service observing. The field was chosen to have a declination of −35°, so that it went roughly overhead at Paranal but meant that the telescope faced south, out of the prevailing wind, minimising the time the field was unobservable due to weather conditions. In 2002 we imaged 40 arcmin^2 to a depth of $R_{AB} = 27.8$, $I_{AB} = 26.5$ and $Z_{AB} = 26$. In 2003 we deepened this field in *Z* to $Z = 26.5$ and imaged a further 40 arcmin^2 to the same depths in the 3 filters. Two more similarly-sized regions should be imaged in 2004, leading to complete imaging of a 160 arcmin^2 region of sky.

Sources that appear to have spectral breaks can be selected from the imaging data. Starting with a flux-limited sample in the *I*-band (to $I_{AB} = 26.3$) we can identify such sources by requiring $R–I > 1.5$ (Fig. 2). To-date we have followed up spectroscopically the sources identified in the 80 arcmin^2 of imaging data we have obtained so far (see Lehnert & Bremer, 2003 for details of the first 40 arcmin^2) . All of these sources meeting the flux and colour criteria, except one, have been observed with FORS2 using the MXU mode. In this mode, a slit mask is inserted in the focal plane that had about about 40 slitlets cut into them. Each one of these slitlets is placed on an object and results in a spectrum.

Observing all these sources meeting this colour criteria, what we found is fascinating. For the objects that were either not detected, or were marginal detection in the R-band, we found that only those sources exhibited signatures suggesting they have redshifts between $4.8 < z < 5.8$ as expected from our simulations (Fig. 3). These signatures were either or both a strong emission line with an asymmetric profile and a break in continuum light. Both the asymmetric line profile, with a tail of emission to the red and a sharp blue edge, and the continuum break are caused by the strong absorption of hydrogen in the intergalactic medium or discrete absorbers (see Fig. 4 for some examples of the spectra). Sources with large breaks but bright magnitudes in R or I were found to be either very red cool stars or intermediate redshift red galaxies (spectral energy distributions and line strengths suggestive of either early type galaxies or heavily extincted star-

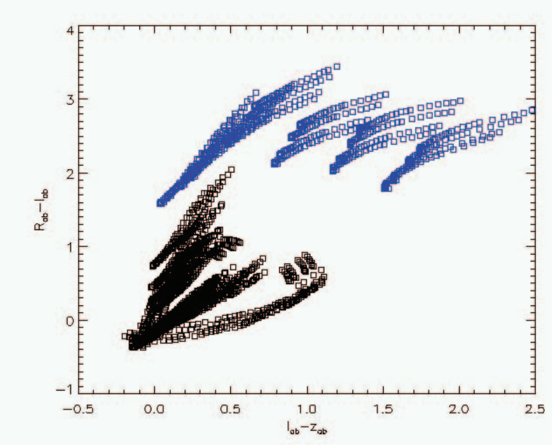


Figure 2: Colour-colour plot of model galaxies with a range of ages and total extinction. The blue squares represent galaxies with redshifts greater than 4.8 while the black squares represent lower redshift galaxies. A colour cut at $R_{ab} – I_{ab}$ is appropriate for selecting high redshift galaxies.

bursts). The number of bright objects meeting the colour criteria in our fields that turned out to be stars or lower redshift galaxies was not large (~5–10). However, compared to the number of high redshift sources with confirmed redshifts, only thirteen out of a total 26 sources, implies that the "contamination rate" is about 1/3. Thus spectroscopy to confirm the nature of the colour selected sources is the key to determining important parameters such as the co-moving space density of high redshift star-forming galaxies. Without the spectroscopy, lower redshift galaxies and stars would make any such estimates very uncertain.

THE PROPERTIES OF HIGH REDSHIFT GALAXIES

In our total field of about 80 arcmin^2 investigated to date, we have determined redshifts for 13 galaxies so far. The Ly-alpha emission from these galaxies (used to determine the redshifts) has fluxes of about few × 10^{-18} to few × 10^{-17} ergs s^{-1} cm^{-2} and has high equivalent widths (>30 angstroms in the rest-frame). The fluxes imply Ly-alpha luminosities of about 10^{42-43} ergs/s and their high emission line equivalent widths suggest very young ages (about to less than 10^8 yrs). However, it is worth noting that inferring such young ages does not rule out the existence of an older population of stars—it simply indicates that the UV continuum relative to the number of ionizing photons is relatively weak but there could be older populations of stars which do not contribute significantly to the UV continuum.

Interestingly, the widths of the Ly-α emission line are relatively modest, being at most several hundred km/s. Signatures of active galactic nuclei (AGN) are broad emission lines or strong high ionization lines of metals. Since we did not detect any broad or high ionization emission lines in any of our spectra, it appears that none of the high redshift sources were AGN. As we shall discuss later, this allows us to put constraints on the number density of relatively low power UV-selected AGN.

The colour and magnitude distribution of the sources without spectroscopic redshifts is very similar to that of the sources with redshifts. This being the case, it is a reasonable assumption that those without spectroscopic redshift are also at similar redshifts. Making this assumption doubles the sample to 26 high redshift galaxies in an area of about 80 arcmin^2. The rest-frame UV flux densities as probed by the *I* and *z*-band fluxes implies that the star-formation rate of the high redshift galaxies is about a few tenths to almost 20 solar masses per year. This is about a factor of a few to 10 higher than the values estimated using the Ly-α luminosities. This is not surprising since Ly-α suffers from both IGM absorption which may

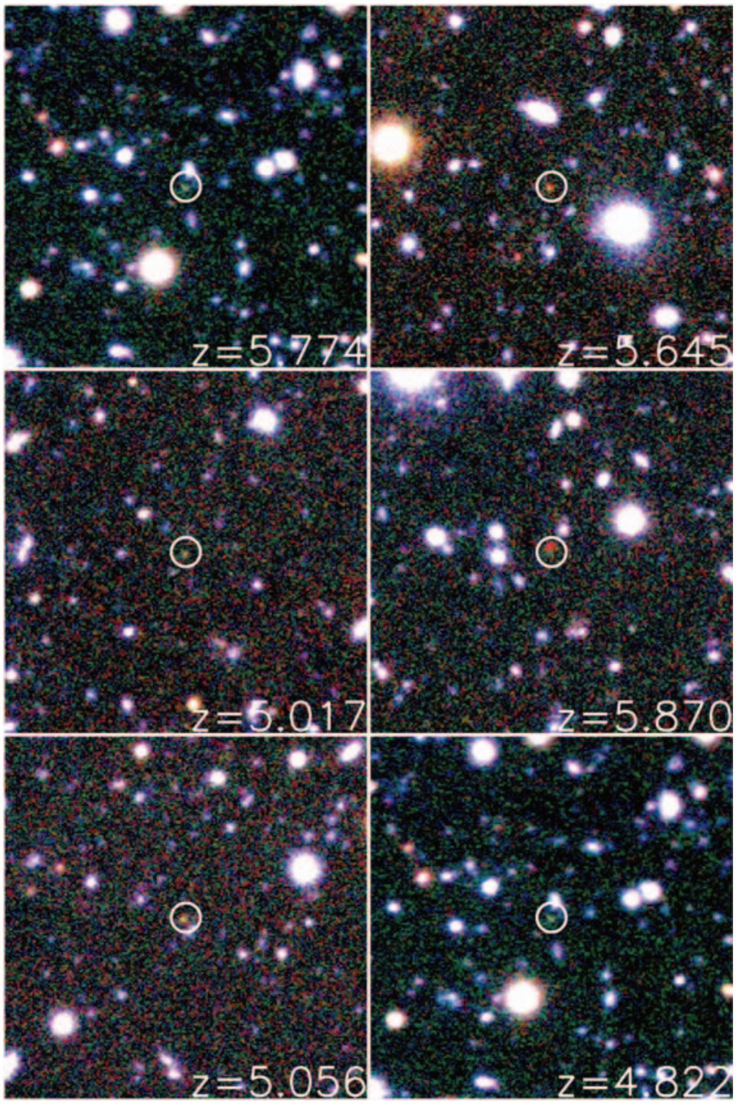


Figure 3: Three colour composites (*R,I,* and *z* are represented as blue, green, and red respectively) of sources with measured redshifts. The circles, which are 2 arc seconds in diameter, are centred on the sources with redshift indicated in the lower left corner of each box.

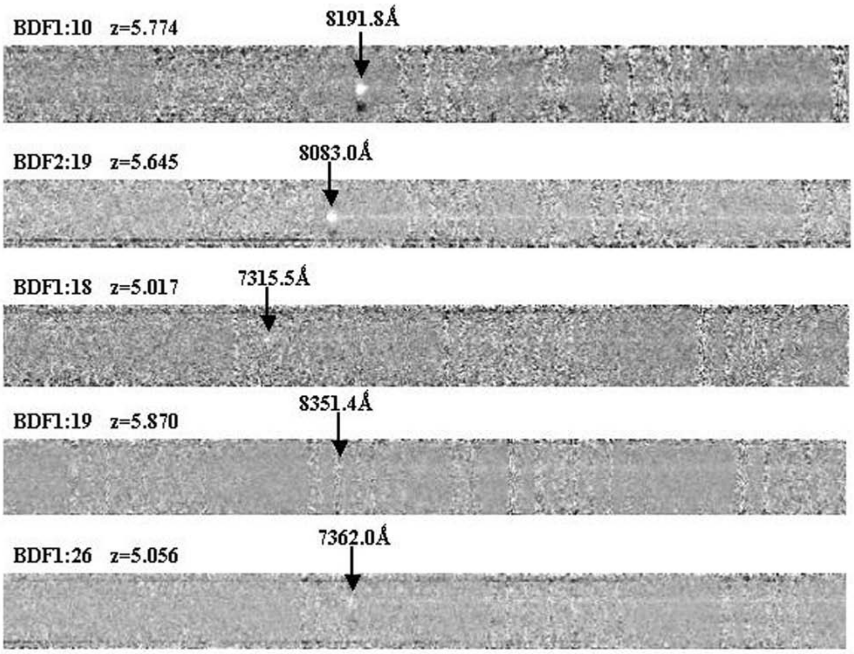
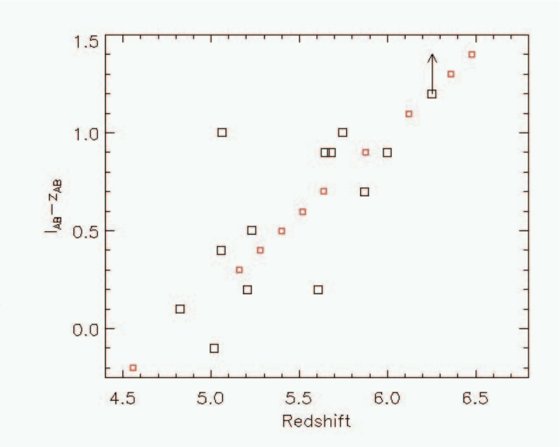


Figure 4: Two dimensional spectra of sources of break galaxies. The name and redshift are indicated above and to the left (blue) end of each spectrum and the wavelength Ly-α emission is indicated by the downward arrow. Continuum emission and then a break is visible in each.

Figure 5: A plot of I-z colour versus redshift. The open black squares show the positions of galaxies with measured redshifts while the small open red squares are the colours of galaxies assuming that I-z = 1.2 • (z-4.8). The colours of the galaxies with and without redshifts over-lap well. The colours compared to galaxy models are consistent with a young population (less than 100 Myrs) and only light extinction. We note that some of the points lie beyond z = 5.8 and were selected as I-band drop-outs with tentative redshifts and are not discussed here.



remove a considerable amount of the intrinsic Ly-α for the high redshift galaxies and, due to high optical depth of the line, radiative transfer effects allow for the destruction of Ly-α by dust grains.

The *I-z* colours of the galaxies also reveal a very interesting trend. We find that the I-z colour correlate with redshift of the sources. Such a trend comes about due to the overwhelming influence of absorption by the IGM and the relatively small dispersion in the intrinsic colours of the sources (Fig. 5). If the colours of the galaxies were intrinsic, then there is no logical reason for such a correlation. It would require something like age or reddening to correlate with redshift which would need to be carefully tuned and thus is ad hoc. Using a model for the IGM (Madau et al. 1996) and galaxy evolutionary synthesis models we can predict the colours of galaxies for a wide range of ages and extinctions, on condition that no galaxy is older than the age of the Universe at redshifts of between 4.8 and 5.8. Doing this we find that the colours of the galaxies as a function of redshift are consistent with them being both young (less than a 100 Myrs) and relatively lightly extincted (visual extinction of a few tenths of a magnitude at most). This result is consistent with the galaxies exhibiting relatively strong Ly-α emission, which due to its fragile nature (because it is easily destroyed by dust), also suggests low extinction. In addition, the high equivalent width of Ly-α also implies relatively young ages for the burst of star formation in the galaxies.

The co-moving space density of high redshift galaxies

Using the estimated number of high redshift galaxies, the area covered in the images, an estimate of the completeness as a function of magnitude, and assumptions about the cosmological parameters, it is possible to estimate the co-moving density of sources. The completeness of the images was estimated using both model images and real images of galaxies with spectroscopically determined redshifts. These individual galaxy or model images were randomly placed in the I-band images of each field and then we tried to "recover" them using a galaxy finding algorithm that was used in originally detecting galaxies within the images. This was done as a function of *I*-band magnitude. In addition, we also checked the detection rate of the general galaxy population by investigating the surface density of sources as a function of magnitude. Only a small fraction of all galaxies are detected near the detection limit of any image. This incompleteness can be estimated by plotting surface density as a function of galaxy magnitude and determining where the number densities begin to deviate from a power-law determined from the bright galaxies in the individual images.

Generally speaking, the co-moving density of objects could now be estimated. However, as discussed earlier, the colours and magnitudes of the sample galaxies are sensitive to the source redshift due to the strong influence of the IGM absorption. Therefore, it is not a simple matter to translate all of the parameters into a co-moving density as a function of magnitude. To mitigate against these effects, we chose a more conservative approach of comparing the co-moving number density of sources at lower redshift selected using a similar technique to the one outlined here. We used the co-moving density as a function of magnitude for a sample of similarly selected galaxies at z~3 and ~4 from Steidel et al. (1999) and applied an offset to the magnitudes due to larger distance of the high redshift sources, put in the incompleteness as determined for the high redshift sample, and then used a linear relationship between *I-z* and redshift covering the range of values we determined for the high redshift sample. What we found is that the number of bright (luminous) galaxies declined significantly from $z \sim 3$ or 4 to $z \sim 5.3$ (the mid-point of our sample). The decline was roughly a factor of 2 to 3.

Although fraught with uncertainty, we can take this analysis one step further. Given that we have the luminosity function of galaxies at $z \sim 3$ or 4 we can then adjust the co-moving density and fiducial luminosity (the luminosity where the functional form of the luminosity function changes from being predominately exponential to predominately a power-law; this luminosity is represented by L^* and the co-moving density by ϕ^*) until we get a good representation of the data. Doing this we find that we need to decrease L^* by about a factor of 3 (or about 1 magnitude) and increase ϕ^* by about a factor of 3. The reason that this is uncertain is that we are only observing galaxies down to about L^* and thus we are not detecting galaxies over a wide portion of the luminosity function.

This analysis indicates that the observed rate of UV photon production per unit volume of observed sources is low compared to the results for lower redshift galaxies. However, by fitting and extrapolating the luminosity function, we find rough agreement. This estimate can then be used to derive a rate of star-formation per unit volume. Making such an estimate for the best fit luminosity function, we again find rough agreement with results for $z = 3$ to 4 galaxies. However, to infer the true rate of star-formation per unit volume, one must correct for extinction. We have found evidence that the extinction in these sources is low, the optical extinction is probably less than a few tenths of a magnitude. If it is this low, then the star-formation rate per unit volume probably declined from z = 3 or 4 to z ~ 5.5 (Fig. 6).

Keeping their Local Volume Ionised and Re-Ionisation

From the UV luminosity function it is possible to estimate the number of ionising photons emitted per unit co-moving volume both by the sources we have directly observed and then by extrapolating to fainter sources using the best-fit luminosity function. Once we have done this we can compare the derived photon density to that required to keep the volume ionized. The UV photon density from our detected sources fell short by a factor of three relative to that produced by similar luminosity galaxies at z~3 and 4. Ferguson et al. (2002) and others had previously shown that even this higher photon density is insufficient to ionize the high redshift Universe.

The clear implication of our analysis is that the objects we have detected emit insufficient ionizing photons to keep their part of the Universe ionized, and so the bulk of ion-

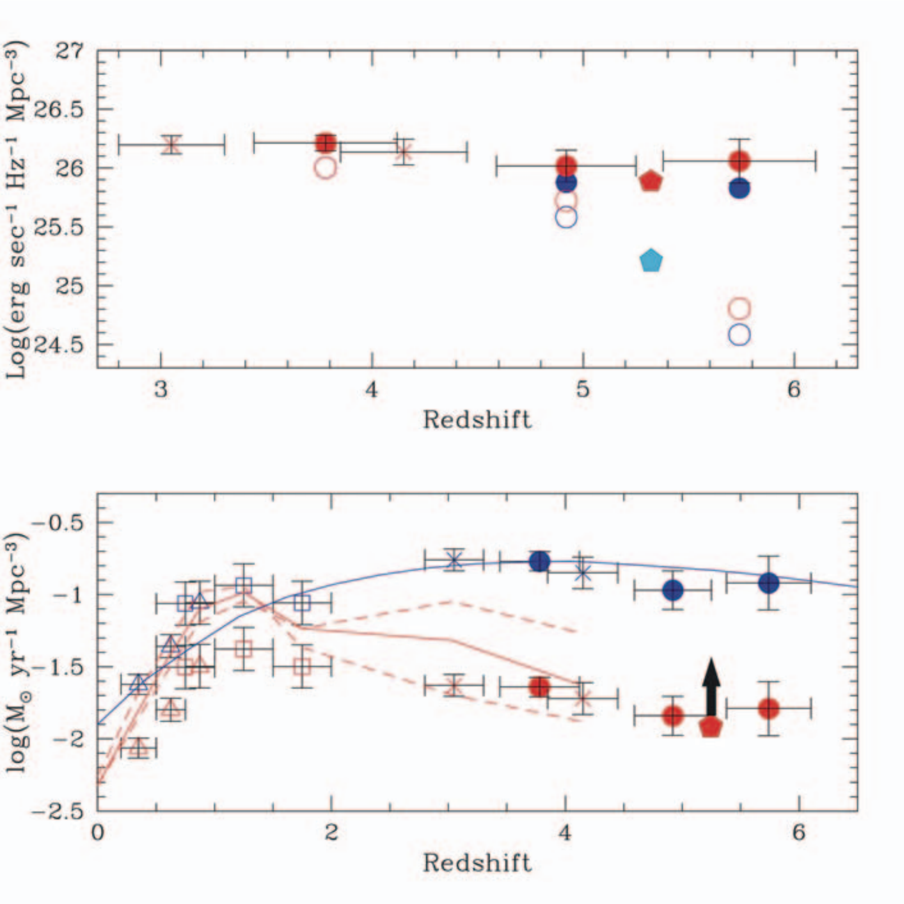


Figure 6: A reproduction of a figure from Giavalisco et al. (2004) of the UV energy density versus redshift (at the top) and the density of star-formation as a function of redshift (at the bottom). The cyan hexagon in the top panel represents the UV energy density we have observed, while the red hexagon is an extrapolation of our best fit luminosity function to low luminosities. In the bottom panel, the red hexagon represents the total star-formation rate density estimated using the extrapolated luminosity density. Giavalisco et al. (2004) applied an extinction correction of 0.8 magnitudes in the visible (blue circles show the extinction correction). Our analysis suggests that something less should be used and the arrow represents a conservative value of 0.4 magnitudes of visual extinction.

izing photons must come from less luminous objects. Given that our sources are observed within 100–200 Myr of the end of reionization, this also implies that the bulk of the photons that reionized the Universe were emitted by relatively low luminosity sources. As we detect no quasars or AGN in our volume, but many galaxies, it follows that unless the AGN luminosity function has a bizarre shape, these less luminous sources must be galaxies. Is there any way that we could have underestimated the ionizing impact of the more luminous detected sources? The photon density required to ionize a volume of IGM depends linearly on the clumping factor of the IGM. Along with many other workers in this field, we assume a clumping factor of 30. Only in the case where this factor is close to unity (in other words, the IGM is completely uniform, clearly ruled out by simulations) does the required photon density become comparable to our measured density. Given the simulations of structure formation at $z > 5$, this is extremely unlikely.

Further work and next steps

As we currently have only ground-based imaging for our field, we followed up this work by searching for similar high redshift dropout galaxies in the HST-ACS data of the GOODS CDF-S field (Bremer et al, 2004). Combining this data with FORS2 and ISAAC imaging of part of the field, we were able to photometrically select and study candidate high redshift galaxies over an area of about 150 arcmin^2. Deep CHANDRA imaging (1 Msec) was available for this field, so we could search for X-ray emission from these sources. This work showed that such sources clustered on scales comparable to that of both our field and the GOODS field, so larger areas of sky needed to be studied to avoid the effects of cosmic variance. Most sources were resolved in the ACS image, but with small effective radii (2 kpc or less at z>5), many looking like the z=5.3 source (or pair of sources) identified in the HDF-N by Spinrad et al (1998). None of the sources were detected in the CHANDRA image, either individually or stacked as an "average" source. This reinforces the result in our earlier work that the sources are star forming galaxies with no evidence of AGN emission. Even if these sources contain obscured AGN, they cannot be powerful sources.

Clearly, there is a great deal more work to be done on understanding these sources and early galaxy formation. With the completion of our 160 arcmin^2 field we will have a field similar in size to the GOODS CDF-S field in order to study clustering on the relatively large scale. With more redshifts (eventually about 25 in this field) we can start to understand the 3-dimensional clustering of the sources, comparing the distributions to detailed simulations of early structure formation. Even then we need to carry out imaging and spectroscopy of other fields over the sky to minimise the impact of cosmic variance. In order to determine the luminosity function with minimal uncertainty we need to obtain many more redshifts (100 or more) in the magnitude range we have studied thus far, and need to securely identify fainter sources. This can be done either by imaging more deeply (such as the imaging being carried out of the ACS-UDF with HST, but over a much larger area to negate cosmic variance), or exploiting the lensing amplification provided by high redshift clusters of galaxies to allow us to probe deeper down the luminosity function. With enough redshifts we may be able to identify evolution in the luminosity function over $z = 4.8$ to $z = 6$, at least crudely. In all of these studies it is clear that the VLT and its instrumentation suite will play a crucial role.

References

Becker, R. et al. 2001, AJ, 122, 2850
Bremer, M., Lehnert M., Waddington I., Hardcastle M., Boyce P., Phillipps, S., 2004, MNRAS, 347, L7
Fan et al. 2001, AJ, 122, 2833
Ferguson, H. C., Dickinson, M., Papovich, C. 2002, ApJ, 569, 65
Giavalisco, M. et al. 2004, ApJ, 600, 103
Gunn J., Peterson B., 1965, ApJ, 142, 1633
Kogut, A. et al. 2003, ApJS, 148, 161
Lehnert M., Bremer M., 2003, ApJ, 593, 630
Madau P., Ferguson H., Dickinson M., Giavalisco M., Steidel C., Fruchter A., 1996, MNRAS, 283, 1388
Scheuer P, 1965, Nature, 207, 963.
Schmidt, M., Schneider, D. P., Gunn, J. E. 1995, AJ, 110, 68
Spinrad et al., 1998, AJ, 116, 2617
Steidel C., Adelberger K., Giavalisco M., Dickinson M., Pettini M.,1999, ApJ, 519, 1