A search for the first massive galaxy clusters

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Abstract. We have obtained deep, multi-band imaging observations around three of the most distant known quasars at redshifts $z > 6$. Standard accretion theory predicts that the supermassive black holes present in these quasars were formed at a very early epoch. If a correlation between black hole mass and dark matter halo mass is present at these early times, then these rare supermassive black holes will be located inside the most massive dark matter halos. These are therefore ideal locations to search for the first clusters of galaxies. We use the Lyman-break technique to identify star-forming galaxies at high redshifts. Our observations show no overdensity of star-forming galaxies in the fields of these quasars. The lack of (dust-free) luminous starburst companions indicates that the quasars may be the only massive galaxies in their vicinity undergoing a period of intense activity.

1 Introduction

The existence of inactive supermassive black holes in the nuclei of massive nearby galaxies (Magorrian et al. 1998) is a sure sign that most galaxies underwent substantial active phases. Furthermore, the correlation between the amount of material accreted (black hole mass) and the galaxy mass indicates important links between galaxy formation and AGN activity. One implication is that the most massive black holes live in the most massive galaxies which reside in the most massive dark matter halos.

The $z > 6$ quasars being discovered in the Sloan Digital Sky Survey (see Fan, this volume) have exceptionally high luminosities ($M_{1450} < -27$). The available evidence suggests that these luminosities are not amplified by gravitational lensing (Fan et al. 2003) or beaming (Pentericci et al. 2002; Willott et al. 2003). Assuming that these quasars are radiating at the Eddington limit gives a lower limit on their black hole masses of several billion solar masses. These are comparable to the black holes inside the largest dominant cluster ellipticals at the present time. Applying local calibrations from this black hole mass to galaxy and halo masses suggests that these quasars reside in halos with mass $\sim 10^{13}\,M_\odot$ (e.g. Fan et al. 2001). LCDM simulations show that structure grows 'bottom-up' with the largest halos typically collapsing at the latest epochs. Halos with mass $> 10^{13}\,M_\odot$ at $z = 6$ are therefore extremely rare (the fraction of mass in such halos is of order 10^{-8}; Sheth & Tormen 1999)

There is evidence that at least some of these quasars are located in massive galaxies. Sub-millimetre photometry of several of them show very high far-infrared luminosities, implying extreme starbursts of $> 1000\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$ (Bertoldi et al. 2003; Priddey et al. 2003). The most distant quasar, SDSS J1148+5251 at $z = 6.42$, contains $\gtrsim 10^{10}\,\mathrm{M}_{\odot}$ of molecular gas, again indicative of a massive, primeval galaxy (Walter et al. 2003). These distant quasars, which are thought to be residing in massive galaxies, are therefore ideal places to search for the first clusters of galaxies. The most straightforward method for identifying galaxies at such high redshifts is the Lyman-break technique – a large discontinuity in the spectral slope due to absorption by neutral hydrogen (e.g. Steidel et al. 1996). The increase in the optical depth of hydrogen absorption at such high redshifts (e.g. Songaila & Cowie 2002) makes the Lyman-break technique even more effective at $z \sim 6$ than at lower redshifts. To search for galaxies in these putative mass overdensities, we carried out a search for Lyman-break galaxies in fields of three $z > 6.2$ SDSS quasars.

2 Observations

We have imaged three quasar fields with the GMOS-North imaging spectrograph on the Gemini-North Telescope: SDSS J1030+0524 at $z = 6.28$, SDSS J1048+4637 at $z = 6.23$ and SDSS J1148+5251 at $z = 6.42$. The imaging field-of-view is 5.5 arcmin on a side, equivalent to a co-moving size of 13 Mpc at $z = 6.3$. Observations were carried out in queue mode during November and December 2003. The typical seeing FWHM of the observations is in the range 0.5 to $0.7''$. Typical exposure times are ≈ 2 hours in the z'-band and ≈ 3 hours in the i'-band. The relative exposure times were designed to give similar sensitivity in the two bands for very red objects with colours of $i' - z' \approx 1.5$. Full details of these observations and their reduction will be published elsewhere.

Detection of objects in the reduced images was performed using the Sextractor software (Bertin & Arnouts 1996). The z'-band was selected as the primary detection waveband since $z > 6$ galaxies are expected to have $i' - z' > 2$ and may therefore be undetected at i'. Sextractor was run in "double-image" mode to determine i'-band measurements for objects detected in z'. Magnitudes on the AB system were measured in circular apertures of diameter $1.5''$. Aperture corrections were applied statistically to the z'-band magnitudes by fitting a linear function to the difference between the total magnitude and aperture magnitude as a function of aperture magnitude. Typical magnitude limits (3σ limits in $1.5''$ apertures) are $z' \approx 26.2$ and $i' \approx 27.6$.

To assess the completeness of the z'-band catalogues we consider both the observed number counts and the recovery of simulated objects. The number counts in the three fields do not differ significantly from each other. They agree well with the z'-band counts determined from a much larger area survey (0.2 square degrees or thirty times the GMOS-North field-of-view) by Capak et al. (2004). The number counts in the quasar fields begin to change slope at $z' > 25.5$ and turn over at $z' = 26$, indicating this is where the sample becomes incomplete.

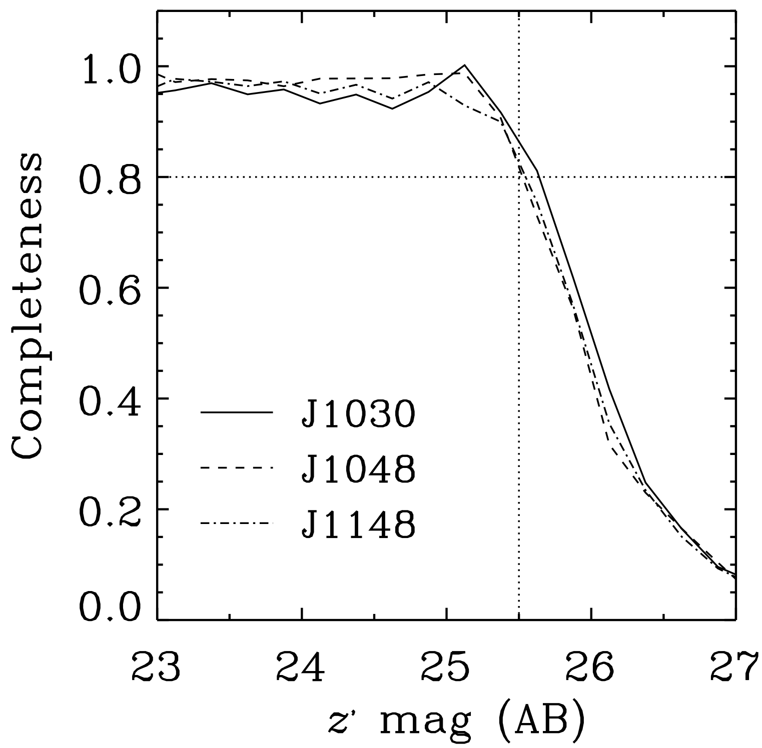

Fig. 1. Completeness ratio against aperture-corrected z'-band magnitude derived from recovery of simulated galaxies. The curves are quite similar for the three different quasar fields. Dotted lines indicate the location of a completeness ratio of 0.8 and the adopted complete magnitude limit of $z' = 25.5$.

The source recovery as a function of magnitude was determined by populating the images with artificial galaxies and then using Sextractor to attempt to detect these objects. About 10 000 artificial galaxies with magnitudes in the range $23 < z' < 27$ were placed into copies of the z' images of each quasar. Regions of the images already occupied by objects were masked out of the process to eliminate incompleteness due to blending. The resulting completeness ratio is plotted as a function of magnitude for the three quasar fields in Fig. 1. The completeness in all the fields is fairly flat at close to 1 up to $z' = 25.2$ and then begins to decline. The rapid decline occurs at $z' > 25.5$ and the completeness drops to 0.5 by $z = 26.0$. All the fields have completeness > 0.8 at $z' = 25.5$ and we adopt this as the magnitude at which completeness begins to become an issue. This analysis with simulated objects agrees well with the results for the number counts discussed previously.

3 High-redshift galaxies in the quasar fields

The $z > 6$ SDSS quasars have $z' \approx 20$ and colours of $i' - z' = 3.25, 2.98, 3.25$ respectively for J1030, J1048 and J1148. Quasars and star-forming galaxies have broadly similar spectra over the rest-frame wavelength range $90 - 140$ nm probed by the i' and z' filters. Their spectra are dominated by a large break due to absorption by neutral hydrogen. Therefore one would expect companion galaxies to have comparable colours to the quasars.

A colour-magnitude diagram for objects in the field of SDSS J1030+0524 is shown in Fig. 2. Most objects have colours in the range $0 < i' - z' < 1$ as is well known from previous surveys (Dickinson et al. 2004; Capak et al. 2004). Also plotted are curves showing the colour-magnitude relation for two different types of galaxy. Model galaxy spectra were generated from the Bruzual & Charlot (2003) spectral synthesis code with Lyman forest absorption evolution matching the observations of Songaila & Cowie (2002). The upper curve is a present-day $L^\star$ elliptical which formed all of its stars in a starburst starting at $z = 10$ with a characteristic timescale of 1 Gyr and evolved since without merging. Note that there is no dust extinction assumed for this model, but in reality the dust extinction would increase with redshift (due to evolution and k-correction) making the galaxy fainter than plotted at higher redshifts. The lower curve is a $L^\star$ Lyman-break galaxy model where the galaxy is observed 0.5 Gyr into a constant star formation rate starburst.

A search was made for objects which could plausibly be high-redshift galaxies. The i'-band dropout selection criteria adopted were snr in the z'-band ≥ 4 and a colour of $i' - z' \geq 1.5$. Possible candidates were inspected and magnitudes checked to ensure their unusual colours are not spurious. A total of four objects satisfying these criteria were found; two in the field of SDSS J1030+0524, shown in Fig. 2 with filled symbols, and one in each of the other two fields. Only one of these four galaxies has a magnitude brighter than the completeness limit of $z' = 25.5$. This object has $i' - z' = 1.56 \pm 0.31$ which is quite close to the colour selection value and the size of the uncertainty means it is quite plausible that photometric errors have scattered the colour into the dropout range. The measured colour is about 5σ away from the colours of the SDSS quasars, which suggests that if it is a high-redshift galaxy, then it is most likely foreground to the quasars with a redshift in the range $5.7 < z < 6$. The other three objects have $z' \approx 25.6$ and only lower limits on their $i' - z'$ colours which lie in the range $1.7 - 1.9$.

Our z'-band images are complete at the greater than 80% level to $z' = 25.5$. At $z' \leq 25.5$, every single z'-band object detected on our images has a counterpart at the $> 3\sigma$ level in the i'-band image. At fainter magnitudes, this is no longer true and our constraints on the $i' - z'$ colours of objects at these magnitudes becomes very weak due to uncertainty in both the z' and i' magnitudes. We now consider the number of i'-band dropouts we could have expected to find under the assumption that the quasar fields are "random" and show no enhancement due to the existence of the quasars. The best comparison dataset which goes deep enough over a wide area is the *Hubble Space Telescope* ACS

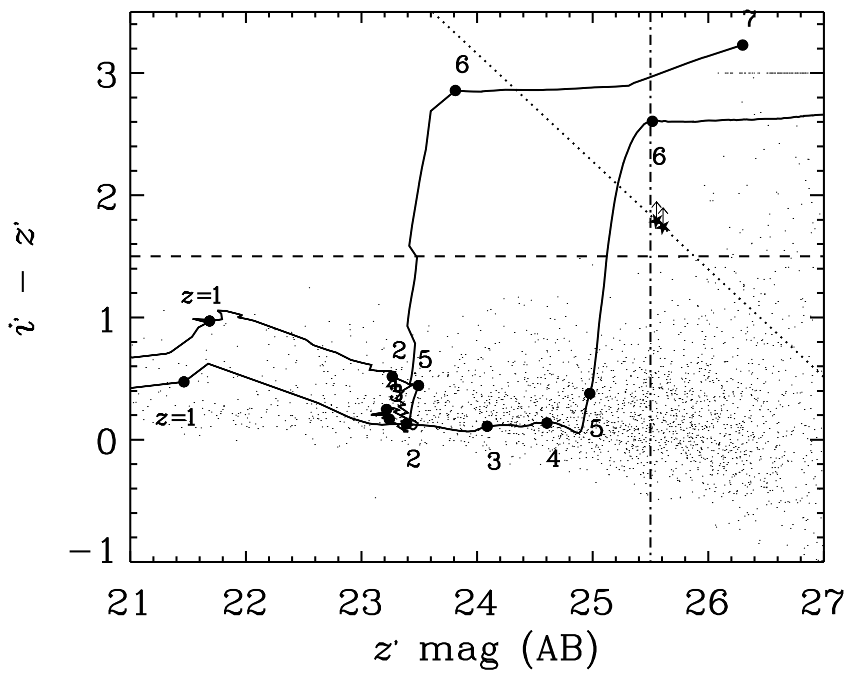

Fig. 2. Colour-magnitude diagram for objects detected at z'-band in the field of the $z = 6.28$ quasar SDSS J1030+0524. The completeness limit of $z' = 25.5$ is shown with a dot-dashed line. The high-redshift galaxy selection criterion of $i' - z' > 1.5$ is marked with the dashed line. The dotted line represents the colour of an object which is just detected at the 3σ level in the i'-band as a function of the z'-band magnitude. Most objects with measured zero or negative flux in the i'-band are plotted at $i' - z' = 3$. The exceptions to this are objects which pass the i'-band dropout selection criteria discussed in the text. These are shown with star symbols and lower limits on the i'-band 3σ line. The dots at $i' - z' > 1.5$ indicate sources which are detected at less than 4σ at z'-band and hence have very large uncertainties on their magnitudes and colours and in some cases may be spurious. The labelled curves show the colour and magnitude as a function of redshift for an evolving L* elliptical (upper curve) and a non-evolving L* Lyman-break galaxy (lower curve) – see text for more details.

imaging of the GOODS regions (Giavalisco et al. 2004). These observations give a surface density of objects with $z' < 25.5$ and $i' - z' > 1.5$ of 0.02 arcmin^{-2} (Dickinson et al 2004; Bouwens et al. 2004). The total sky area we have surveyed with GMOS-North is 82 arcmin^2. Therefore on the basis of the GOODS observations we would expect 1.6 i'-band dropouts in our total area. Our finding of one dropout is entirely consistent with the expectations for blank fields.

Our observations show that these quasar fields do not exhibit an excess of luminous companion galaxies. The magnitude limit of $z' = 25.5$ corresponds to a UV luminosity of $L_{1500} = 2.5 \times 10^{29}$ergs^{-1}Hz^{-1} at a redshift of $z = 6.3$. This is equivalent to an unobscured star formation rate of $SFR = 30$ M$_\odot$ yr^{-1}, assuming the conversion given in Madau, Pozzetti & Dickinson (1998). The few known galaxies at redshifts $z \approx 6.6$ discovered in narrow-band surveys have star formation rates derived from their UV luminosities comparable to this limit (Hu et al. 2002; Kodaira et al. 2003). For comparison, the millimeter detections of dust in J1048 and J1148 imply total star formation rates > 1000 $M_\odot yr^{-1}$ in the host galaxies of the quasars (Bertoldi et al. 2003).

How do we explain the lack of companion galaxies with high star formation rates? One possibility is that galaxies undergoing intense star formation do exist but they are heavily extinguished by dust. Such galaxies may be detectable via their far-infrared emission and we are conducting a program of sub-mm imaging around these quasars to identify such galaxies. Deep observations with the IRAC camera on the *Spitzer Space Telescope* would also be able to reveal these obscured galaxies. Another possibility is that massive companion galaxies exist but they are not observed during a period of intense star formation. This possibility seems unlikely since the youth of the universe at this redshift means galaxies would likely be gas-rich and forming stars, especially if located in a dense environment which is not yet virialized. Finally, we raise a question mark over the notion that these rare massive black holes actually reside in the rarest, densest peaks in the dark matter distribution. Perhaps the correlation between black hole mass and dark matter halo mass (or halo circular velocity – see Wyithe & Loeb 2004) does not apply to these quasars and they are actually located inside less massive dark matter halos.

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