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Discovery of a radio galaxy at $z = 5.72$

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ABSTRACT

We report the discovery of the most distant radio galaxy to date, TGSS1530 at a redshift of $z = 5.72$ close to the presumed end of the Epoch of Reionisation. The radio galaxy was selected from the TGSS ADR1 survey at 150 MHz for having to an ultra-steep spectral index, $\alpha_{1.4\text{ GHz}}^{150\text{ MHz}} = -1.4$ and a compact morphology obtained using VLA imaging at 1.4 GHz. No optical or infrared counterparts for it were found in publicly available sky surveys. Follow-up optical spectroscopy at the radio position using GMOS on Gemini North revealed the presence of a single emission line. We identify this line as Lyman alpha at $z = 5.72$, because of its asymmetric line profile, the absence of other optical/UV lines in the spectrum and a high equivalent width. With a Ly α luminosity of 5.7×10^{42} erg s⁻¹ and a FWHM of 370 km s⁻¹, TGSS1530 is comparable to ‘non-radio’ Lyman alpha emitters (LAEs) at a similar redshift. However, with a radio luminosity of $\log L_{150\text{ MHz}} = 29.1$ W Hz⁻¹ and a deconvolved physical size 3.5 kpc, its radio properties are similar to other known radio galaxies at $z > 4$. Subsequent *J* and *K* band imaging using LUCI on the Large Binocular Telescope resulted in non-detection of the host galaxy down to 3σ limits of $J > 24.4$ and $K > 22.4$ (Vega). The *K* band limit is consistent with $z > 5$ from the *K* – z relation for radio galaxies, suggesting stellar mass limits using simple stellar population models of $M_{\text{stars}} < 10^{10.5} M_{\odot}$. Its high redshift coupled with relatively small radio and Ly α sizes suggest that TGSS1530 may be a radio galaxy in an early phase of its evolution.

Key words: radio galaxies – high redshift – spectroscopy

1 INTRODUCTION

Powerful radio galaxies have been shown to be robust beacons of the most massive galaxies across cosmic time. High-redshift radio galaxies (HzRGs) are thought to be the progenitors of the local massive elliptical galaxies. HzRGs generally contain large amounts of dust and gas (Best et al. 1998; Carilli et al. 2002a; Reuland et al. 2004; De Breuck et al. 2010) and are among the most massive galaxies at their redshift (Overzier et al. 2009). HzRGs are often found to be located at the centre of clusters and proto-clusters of galaxies (Pentericci et al. 2000; Venemans et al. 2002; Röttgering

et al. 2003; Miley et al. 2004; Hatch et al. 2011; Orsi et al. 2016) and studies of their environment can give insights into the assembly and evolution of the large scale structure in the Universe. Miley & De Breuck (2008) provide an extensive review about the properties of distant radio galaxies and their environments.

Radio galaxies at $z > 6$, in the Epoch of Reionisation (EoR), are of particular interest as they could be used as unique tools to study the process of reionisation in detail. At these redshifts, the 21cm hyper-fine transition line of neutral hydrogen falls in the low-frequency radio regime and can in principle be observed in absorption in the spectra of luminous background radio sources, such as radio galaxies (Carilli et al. 2002b; Furlanetto & Loeb 2002; Xu et al. 2009;

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Mack & Wyithe 2012; Ewall-Wice et al. 2014; Ciardi et al. 2015). Such 21cm absorption signals from patches of neutral hydrogen clouds in the early Universe could in principle be observed by current and next-generation radio telescopes such as the Low Frequency Array (LOFAR), the Murchinson Widefield Array and the Square Kilometer Array (SKA). This unique application motivates searches for radio galaxies at the highest redshifts from deep, all-sky radio surveys at low radio frequencies.

Finding powerful radio galaxies at increasingly large distances or redshifts, however, is challenging. They are among the rarest objects in the Universe and flux-limited samples have shown that the space densities of bright radio galaxies fall off dramatically at $z > 2 - 3$ (Dunlop & Peacock 1990; Willott et al. 2001; Rigby et al. 2011, 2015). Therefore, large area surveys are essential to gather enough statistics for meaningful studies of radio galaxies at high redshifts. Fainter all-sky surveys at low radio frequencies, such as the TIFR GMRT Sky Survey Alternative Data Release 1 (TGSS; Intema et al. 2017) and the currently ongoing surveys using LOFAR (Shimwell et al. 2017) are opening up new parameter spaces for searches for radio galaxies at $z \geq 6$ (Saxena et al. 2017).

The previously known most distant radio galaxy is TN J0924–2201 (referred to as TNJ0924 from here on) at $z = 5.2$ (van Breugel et al. 1999). With the availability of TGSS covering the radio sky north of -53 declination at a frequency of 150 MHz and achieving a median noise level of $3.5 \text{ mJy beam}^{-1}$, we launched a campaign to hunt for fainter and potentially more distant HzRGs, with the ultimate aim of discovering radio galaxies that could be suitable probes of the EoR (Saxena et al. 2018). In this paper, we report the discovery a radio galaxy at a redshift of $z = 5.72$, TGSS1530, which was pre-selected as part of our sample of high-redshift radio galaxy candidates.

The layout of this paper is as follows. In Section 2 we present details about the initial source selection criteria and the follow-up radio observations at high resolution for TGSS1530. In Section 3 we present the new optical spectroscopy and infrared imaging obtained for TGSS1530 and expand upon the data reduction methods. In Section 4 we describe how the redshift for this source was determined. In Section 5 we study the emission line and radio properties of this source and set constraints on its stellar mass. We also compare the observed properties to galaxies at the same epoch from the literature. Finally, in Section 6 we summarise the findings of this paper. Throughout this paper we assume a flat Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_m = 0.3$. Using this cosmology, at a redshift of 5.72 the age of the Universe is 0.97 Gyr, and the angular scale per arcsecond is 5.86 kpc.

2 SOURCE SELECTION

Our two stage selection process is based on first isolating compact radio sources with an ultra-steep spectrum (USS; $\alpha < -1.3$, where $S_\nu \propto \nu^\alpha$) at radio wavelengths, that has historically been very successful at finding HzRGs from wide area radio surveys (Röttgering et al. 1994; Blundell et al. 1999; De Breuck et al. 2000; Afonso et al. 2011), and then combining it with optical and/or infrared faintness require-

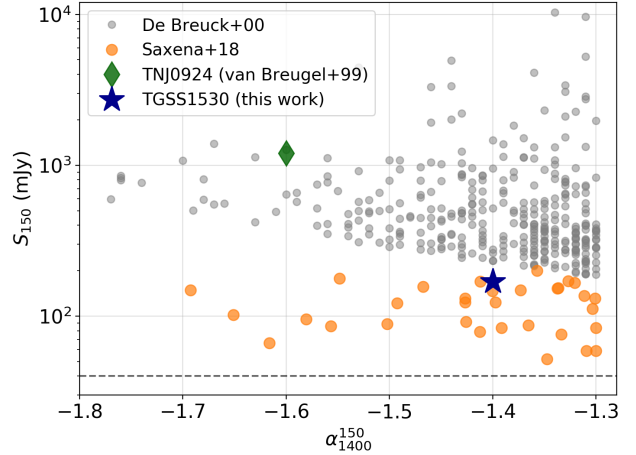


Figure 1. The location of TGSS1530 in the flux density–spectral index parameter space. The large orange points show the parameter space probed by the Saxena et al. (2018) sample and the smaller grey points show radio sources from De Breuck et al. (2000), scaled to an observed frequency of 150 MHz using the spectral indices provided for individual sources. Also shown for comparison is TNJ0924 at $z = 5.2$ (van Breugel et al. 1999). TGSS1530 is fainter than the previously studied large area samples and offers a new window into fainter radio galaxies at high redshifts.

ments. The relation that exists between the apparent K -band magnitude of radio galaxies and their redshift, known as the $K-z$ relation, (Lilly & Longair 1984; Jarvis et al. 2001; Willott et al. 2003; Rocca-Volmerange et al. 2004) gives further strength to the argument of selecting USS sources that are also faint at near-infrared wavelengths in a bid to isolate HzRGs (Ker et al. 2012). Deep near-infrared imaging of promising USS candidates can therefore serve as an independent way to set constraints on the redshifts of radio sources. HzRGs are expected to be very young and therefore, have small sizes at the highest redshifts (Saxena et al. 2017): implementing an additional criterion that puts an upper limit on the angular sizes of radio sources has the potential to increase the efficiency of pin pointing the highest-redshift sources in an all-sky radio survey.

Combining all of these selection methods, we compiled a sample of 32 promising HzRG candidates selected at 150 MHz from TGSS with an ultra-steep spectrum ($\alpha_{1.4 \text{ GHz}}^{150 \text{ MHz}} < -1.3$) and compact morphologies. This sample probes fainter flux densities than previous large area searches and has flux limits that ensure that a new parameter space in flux density and spectral index is probed where potentially a large number of undiscovered HzRGs are expected to lie (Ishwara-Chandra et al. 2010). We only retained in our sample radio sources that are blank in all available optical surveys such as the Sloan Digital Sky Survey DR12 (SDSS; Alam et al. 2015) and the Pan-STARRS1 survey (PS1; Chambers et al. 2016), and infrared surveys such as ALLWISE using the WISE satellite (Wright et al. 2010) and the UKIDSS surveys (Lawrence et al. 2007) to maximise the chances of finding radio galaxies at the highest redshifts. Details of the sample selection can be found in Saxena et al. (2018).

High resolution imaging using the Karl G. Jansky

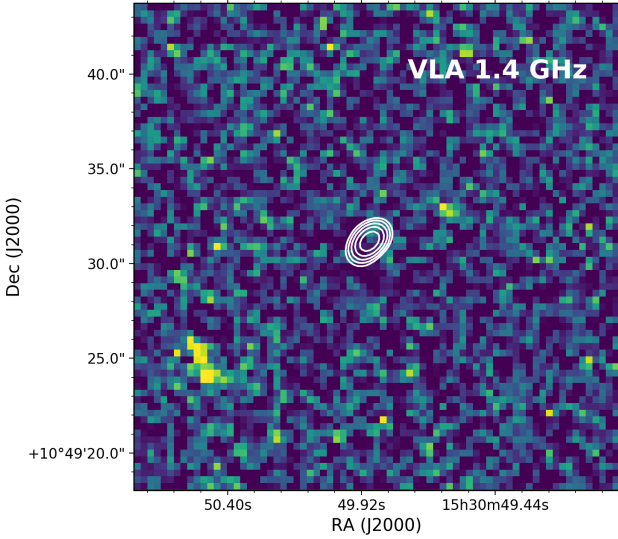


Figure 2. Stacked y , J , H and K band image from the UKIDSS Large Area Survey, with contours (starting from 0.5 mJy, in a geometric progression of $\sqrt{2}$) from the 1.4 GHz VLA map (Saxena et al. 2018) overplotted for TGSS1530. The radio source is compact and has an ultra-steep spectral index. A non-detection in the UKIDSS LAS K band down to a magnitude limit of 18.4 Vega (~ 20.3 AB) made TGSS1530 a promising HzRG candidate and a prime target for spectroscopic follow-up.

Very Large Array (VLA) for the 32 candidates, including TGSS1530 (RA: 15:30:49.9, Dec: +10:49:31.1) is presented in Saxena et al. (2018), which was used to obtain morphologies and sub-arcsecond localisation of the expected positions of the host galaxies, enabling blind spectroscopic follow-up. TGSS1530 in particular showed a compact morphology, which was fitted with a single Gaussian. With a flux density of $S_{150\text{ MHz}} = 170 \pm 34$ mJy, TGSS1530 is one of the brightest sources in the sample. At 1.4 GHz, it has a flux density $S_{1.4\text{ GHz}} = 7.5 \pm 0.1$ mJy, giving a spectral index of $\alpha = -1.4 \pm 0.1$. With a relatively small (deconvolved) angular size of 0.6 ± 0.1 arcsec, TGSS1530 was deemed to be a promising HzRG candidate. We show the location of TGSS1530 in the flux density–spectral index parameter space in Figure 1.

TGSS1530 is not detected in any of the PS1 bands (g , r , i , z and y). This source also happens to lie in the sky area covered by the UKIDSS Large Area Survey (LAS), and is not detected down to (Vega) magnitude limits of $y > 20.5$, $J > 20.0$, $H > 18.8$ and $K > 18.4$. We show the image obtained from stacking all of the LAS bands with radio contours overlaid in Figure 2. Lastly, this source is also not detected in any of the ALLWISE bands. These non-detections coupled with the ultra-steep radio spectral index and compact radio morphology are in line with expectations of a high-redshift host galaxy and made TGSS1530 a prime candidate for follow-up spectroscopy.

3 OBSERVATIONS

3.1 Gemini GMOS spectroscopy

A long-slit spectrum of TGSS1530 was taken using GMOS on Gemini North on 28 April, 2017 (Program ID: GN-2017A-Q-8; PI: Overzier) using the filter GG455_G0305 and the R400_G5305 grating giving a resolution of roughly $R \sim 1500$. The central wavelength was set to 700 nm. The total length of the slit was 300 arcseconds and the slit width was chosen to be 1.5 arcseconds so that it covers the entire radio emission footprint detected in the VLA image. As the host galaxy of the radio source was undetected in all available all-sky optical/IR surveys, we performed blind offsetting from a bright star, which ensures positional accuracy to within 0.1 arcseconds, to the centroid of the radio emission. The VLA observations ensured sub-arcsecond localisation of the expected position of the host galaxy and the relatively large slit-width provided insurance against minor positional uncertainties. We took 3 exposures of 800 seconds each, giving a total of 2400 seconds of on-source exposure time. The standard star EG131 was observed for flux calibration.

We used the Gemini IRAF package for reducing the data, which includes the standard steps for optical spectrum reduction. Briefly, the bias frames were mean stacked in a master bias which was subtracted from all other images acquired. Pixel-to-pixel sensitivity was corrected through the flat field image taken during the day of the observations. The wavelength solution was derived from the arc lamp frame taken immediately after the science observations, and applied to the science frame and standard star. The 2D images were then combined in a single frame, rejecting possible cosmic rays. The sky lines were removed and flux calibration was achieved using the standard star spectrum.

A single emission line with a peak at 8170 \AA and a spatial extent of ~ 1 arcsecond was detected in the reduced 2D spectrum at the expected position of the radio galaxy. No other line associated with this source was detected. No continuum was detected either bluewards or redwards of this line either. To ensure that the line detection is indeed real and not due to an artefact or contamination by cosmic rays, we looked at the individual frames, both raw and sky subtracted, to ensure that the detection (although marginal) was present in each science frame. The three frames are shown in Figure 3. The top panels show the raw frames and the bottom panels the sky subtracted frames. The emission line is clearly present in all three frames, ensuring that the detection is real. The extracted 1D spectrum with a 1 arcsecond aperture showing the detected emission line is shown in Figure 4. We give details about line identification in Section 4.

3.2 Large Binocular Telescope NIR imaging

Imaging in the J and Ks bands using LUCI (formerly known as LUCIFER; Seifert et al. 2003) on the Large Binocular Telescope (LBT) was carried out in two separate runs, with the first on 1 February 2018 and the second on 11 May 2018 (Program ID 2017_2018_43; PI: Prandoni). The average seeing throughout the observations was $0.6 - 0.8$ arcseconds. In the first run, the on-source exposure time was 720 (12×60) seconds in J (central wavelength of 1.247 microns) and

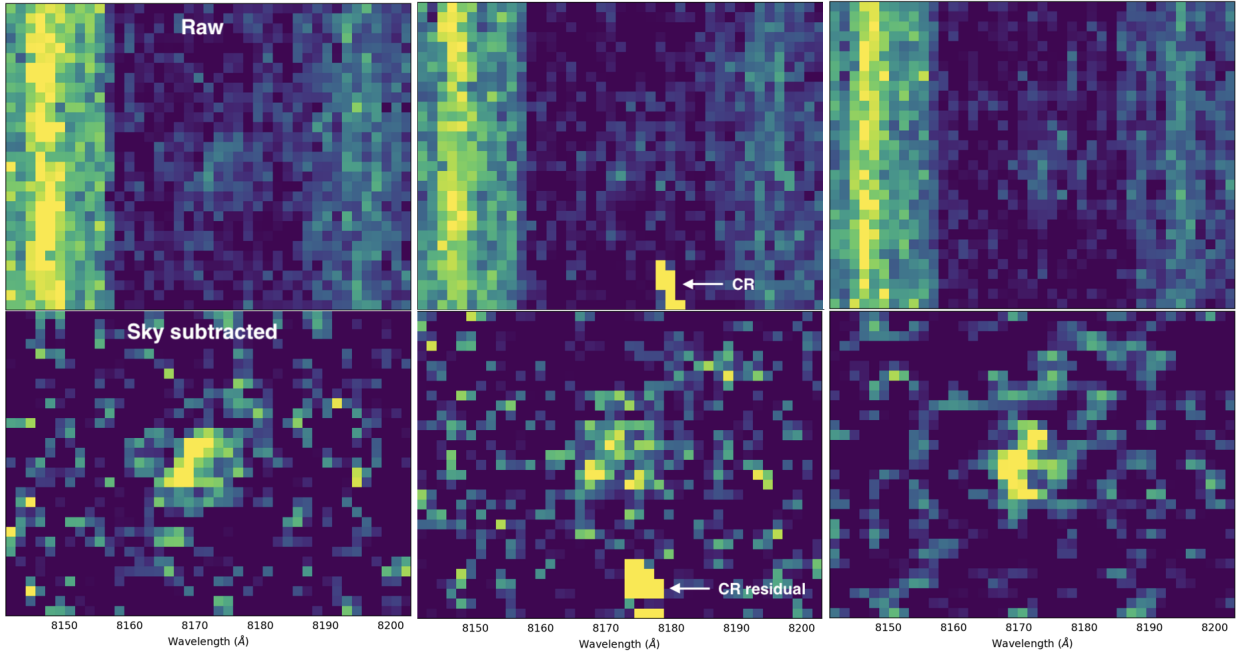


Figure 3. Raw (top panels) and sky subtracted (bottom panels) 2D frames shown for the three individual exposures taken using GMOS on Gemini. Traces of the emission line are visible in all three frames, ensuring that the detected line is real and not a consequence of cosmic rays or artefacts. There is some cosmic ray residual left over in the second frame but that does not contaminate the emission line signal.

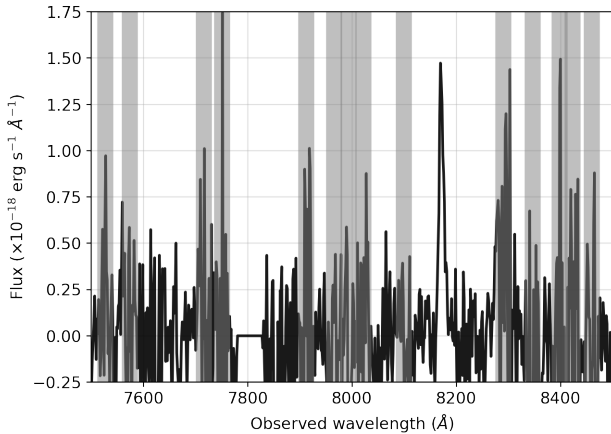


Figure 4. Extracted 1D spectrum showing the single emission line detection centred at 8170 Å from the GMOS 2D spectrum. No other line or continuum is detected. Shaded regions mark the presence of sky lines in the spectrum.

1200 (20×60 s) seconds in K_s (central wavelength of 2.194 microns). In the second run we obtained additional 3600 (30×120 s) seconds in J and 3000 (50×60 s) seconds in K_s , giving a total on-source exposure time of 4320 seconds in J band and 4200 seconds in K_s band.

The LUCI data reduction pipeline developed at INAF-OAR was used to perform the basic reduction such as dark subtraction, bad pixel masking, cosmic ray removal, flat

fielding and sky subtraction. Astrometric solutions for individual frames were obtained and the single frames were then resampled and combined using a weighted co-addition to form a deeper image. The $4' \times 4'$ field-of-view of LUCI contained many bright objects detected in both 2MASS and the UKIDSS Large Area Survey, which were used to calibrate the photometry of the images in both bands.

The median and standard deviation of the background in both images was calculated by placing 5000 random apertures with a diameter of 1.5 arcseconds. We measure 3σ depths of $J = 24.4$ and $K_s = 22.4$. Aperture photometry performed on both J and K_s (from here on we denote K_s as simply K) images using PHOTUTILS (Bradley et al. 2017) at the peak of the radio emission using an aperture of diameter 1.5 arcseconds yield magnitudes that are lower than the 3σ depths in both images. Smoothing the K band image with a 3×3 pixel Gaussian kernel reveals a faint source very close to the peak radio pixel, as shown in Figure 5, but it is not entirely clear if this indeed the host galaxy and there is no faint detection even in the smoothed J band image. A summary of the observations is given in Table 1.

4 REDSHIFT DETERMINATION

We identify the single emission line detected in the GMOS spectrum as Ly α λ 1216, giving a redshift of $z = 5.720 \pm 0.001$, which is shown in Figure 6. Other plausible identifications of this emission line could be [O III] λ 5007, giving a redshift of $z \approx 0.63$ or H α λ 6563 at $z \approx 0.25$. These can be ruled out given the non-detection of other bright lines expected in the

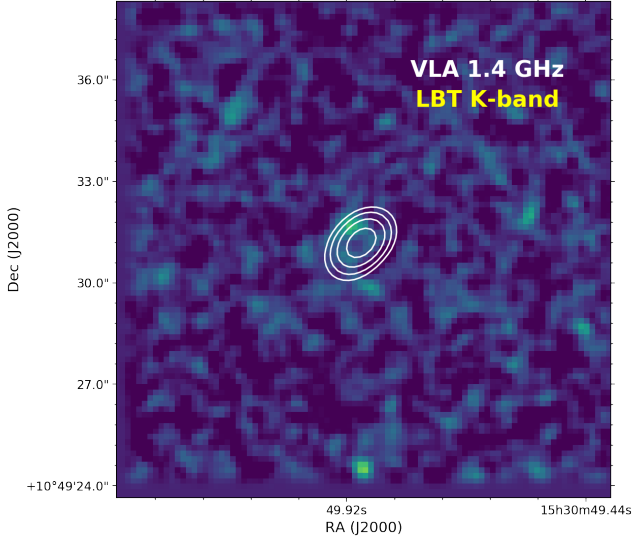


Figure 5. K -band image from the Large Binocular Telescope (LBT), which has been smoothed with a 3×3 pixel Gaussian kernel, with radio contours (same as Figure 2) from the VLA at 1.4 GHz overlaid. The measured magnitude at the radio position with a 1.5 arcsecond aperture is fainter than the 3σ depth of the image, giving $K > 22.4$. When the image is smoothed, however, faint emission is visible around the peak of the radio emission. The magnitude limit is consistent with $z > 5$ following the $K - z$ relation for radio galaxies. For comparison, the $z = 5.2$ radio galaxy TN J09224–2201 has a K -band magnitude of 21.3 (van Breugel et al. 1999).

Table 1. Observation log.

Telescope	Instrument	Date	Exp. time (sec)
Gemini N	GMOS long-slit	28-04-2017	2400 (3×800 s)
LBT	LUCI J-band	01-02-2018	720 (12×60 s)
		09-05-2018	3600 (30×120 s)
	Total		4320
LBT	LUCI Ks-band	01-02-2018	1200 (20×60 s)
		09-05-2018	3000 (50×60 s)
	Total		4200

wavelength range covered. An unresolved [O II] $\lambda\lambda 3726, 3729$ doublet at a redshift of $z \approx 1.2$ could be a possibility, but the absence of other expected UV/optical lines common in AGN and radio galaxy spectra, such as C II] $\lambda 2326$ or Mg II $\lambda\lambda 2797, 2803$, which are on average a factor of 2–4 times fainter than [O II] (De Breuck et al. 2000), makes this possibility unlikely.

We fit a Gaussian to the emission line (shown in Figure 6) to measure an integrated line flux of $F_{Ly\alpha} = 1.6 \pm 0.2 \times 10^{-17}$ erg s $^{-1}$ cm $^{-2}$. The total measured Ly α luminosity is $L_{Ly\alpha} = 5.7 \pm 0.7 \times 10^{42}$ erg s $^{-1}$. The full width at half maximum (FWHM) after correcting for the instrumental FWHM is 370 ± 30 km s $^{-1}$. Since no continuum is detected in the spectrum (down to 1σ depth of 4.0×10^{-19} erg s $^{-1}$ cm $^{-2}$), we can only put a lower limit on the rest-frame equivalent

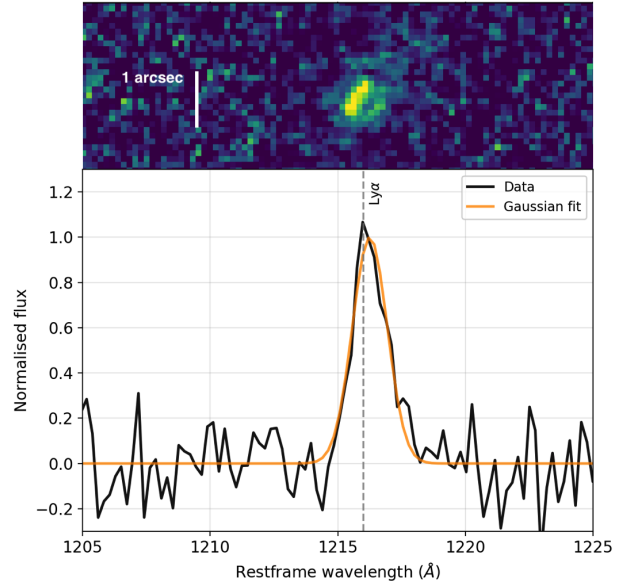


Figure 6. Rest-frame 1D spectrum showing the asymmetric Ly α line profile at a redshift of $z = 5.72$. Also shown is the best-fit Gaussian to the emission line. The peak of the fitted Gaussian is slightly redder than the peak of the line, suggesting asymmetry in the emission line. This is also clear from the excess towards the redder parts of the Gaussian. *Top:* The 2D GMOS spectrum showing the detected Ly α line. The spatial extent of the emission is roughly 1 arcsecond, which is also the aperture size used to extract the 1D spectrum.

width (EW) of the line, $EW_0 > 40 \text{ \AA}$. Table 2 presents a summary of emission line measurements for TGSS1530.

4.1 Skewness and equivalent width

To further confirm our redshift determination, we quantify the asymmetry of the emission line following the prescriptions laid out by Kashikawa et al. (2006), by calculating the S-statistic and the weighted skewness parameter. A measure of the skewness of the emission line is particularly useful when dealing with spectra with a single emission line and can help differentiate Ly α emission at high redshifts from [O II], [O III] or H α emission from lower redshift galaxies (Rhoads et al. 2003; Kurk et al. 2004; Kashikawa et al. 2006). We measure the skewness $S = 0.31 \pm 0.14$ and the weighted skewness $S_w = 6.44 \pm 2.97 \text{ \AA}$, which are consistent with what is observed for confirmed Ly α emitters at high redshift (Kashikawa et al. 2006, 2011; Matthee et al. 2017).

To check what possible values of skewness could be obtained from an unresolved [O II] doublet, we simulated the doublet with all possible ratios ($0.35 < j_{\lambda 3729}/j_{\lambda 3726} < 1.5$), convolved with the instrument resolution. We find that the skewness measured for the emission line seen in the spectrum ($S = 0.31$) is only possible for $j_{\lambda 3729}/j_{\lambda 3726} < 0.7$. These line ratios correspond to the high electron density regime when the line would be collisionally de-excited, and hence unlikely to be as strong as observed, with previous studies of the [O II] doublet in high- z galaxies (Steidel et al. 2014; Shimakawa et al. 2015; Sanders et al. 2016) also finding much higher line

Table 2. Spectroscopic redshift and emission line measurements for TGSS1530 through GMOS spectroscopy.

Property	Measurement
z_{spec}	5.720 ± 0.001
$F_{\text{Ly}\alpha}$	$1.6 \pm 0.2 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$
$L_{\text{Ly}\alpha}$	$5.7 \pm 0.7 \times 10^{42} \text{ erg s}^{-1}$
FWHM	$370 \pm 30 \text{ km s}^{-1}$
EW_{obs}	$> 40 \text{ \AA}$

ratios on average. This helps drive the interpretation of the observed emission line more towards a Ly α at high redshift.

Further, an $\text{EW} > 40 \text{ \AA}$ for an [O II] line originating from a presumably massive radio galaxy at $z \approx 1.2$ would be at the extreme end of the EW distribution (Bridge et al. 2015), including for radio-loud quasars (Kalfountzou et al. 2012). This EW value is also incompatible with the line ratios that would give rise to the observed skewness, as in regions of very high electron densities the [O II] line is expected to be weaker due to collisional de-excitation. Therefore, we can practically rule out the [O II] doublet as a possible identification of this emission line. An $\text{EW}_0 > 40 \text{ \AA}$, however, is typical for Ly α emission seen in galaxies at $z \approx 5.7$ (see Kashikawa et al. 2011, for example) and generally consistent with the $z \sim 6$ galaxy population (De Barros et al. 2017).

4.2 K-z relation for radio galaxies

Finally, a strong indicator of a high-redshift nature of the host galaxy is the non-detection in K band down to a 3σ limiting magnitude of 22.4 (Figure 5) using aperture photometry at the peak pixel of the radio emission. For comparison, TNJ0924 at $z = 5.2$ has a magnitude of $K = 21.3 \pm 0.3$ and our measurement of $K > 22.4$ is consistent with $z > 5$ and helps rule out lower redshifts owing to the $K - z$ relation for radio galaxies (note that the luminosity and the spectral index rule out that it is a star-forming galaxy). We expand upon this point in Section 5.3. The additional non-detection in J band down to a 3σ limit of 24.3 further favours a high redshift galaxy and supports the argument that the line we see is indeed Ly α and not [O II].

5 DISCUSSION

5.1 Emission line measurements

The Ly α luminosity and FWHM measured for TGSS1530 are lower than what is seen for typical HzRGs at $z > 4$ (see Spinrad et al. 1995; De Breuck et al. 1999; van Breugel et al. 1999; Miley & De Breuck 2008, for examples) and more consistent with those measured for ‘non-radio’ Ly α emitting galaxies (LAEs) at this redshift (Rhoads et al. 2003; Ouchi et al. 2008; Kashikawa et al. 2011; Lidman et al. 2012; Matthee et al. 2017). However, the FWHM for TGSS1530 is consistent with that of a very faint radio galaxy VLA J123642+621331, with a 1.4 GHz flux density of $S_{1.4 \text{ GHz}} = 0.47 \text{ mJy}$, discovered at $z = 4.424$ (Waddington et al. 1999). This galaxy has a FWHM of $\approx 420 \text{ km s}^{-1}$ and a Ly α luminosity $\approx 2 \times 10^{42} \text{ erg s}^{-1}$, which is weaker

than TGSS1530. VLA J123642+621331 is however, not detected in TGSS at 150 MHz down to a noise level of $3.5 \text{ mJy beam}^{-1}$, suggesting a relatively flat spectral index or a spectral turnover at low radio frequencies. We present some comparisons of the Ly α properties we measure for TGSS1530 with other HzRGs at $z > 4$ and also non-radio LAEs at $z = 5.7$ in Table 3.

A statistical sample of radio galaxies at $z \sim 6$ is needed to understand whether they are more like LAEs at high redshift or whether a majority of them continue being very different systems, surrounded by extremely overdense regions and forming stars intensively. The relatively underluminous Ly α would be one signature of a significantly neutral intergalactic medium (IGM) during the late stages of the EoR. Weaker Ly α emission may also be caused by significant absorption in a cold and dusty medium surrounding the radio galaxy. The presence of cold gas and dust has been reported in many HzRGs, including TNJ0924 (see Klammer et al. 2005, for example) and dedicated observations to look for molecular gas and dust in a statistically significant sample of radio galaxies at $z > 5$ are required to better characterise their surrounding medium.

5.2 Radio properties

TGSS1530 has a flux density of 170 mJy at a frequency of 150 MHz and 7.5 mJy at 1.4 GHz (Saxena et al. 2018). Using the standard K -corrections in radio astronomy and assuming a constant spectral index of $\alpha = -1.4$, we calculate a rest-frame radio luminosity of $\log L_{150 \text{ MHz}} = 29.1$ and $\log L_{1.4 \text{ GHz}} = 28.2 \text{ W Hz}^{-1}$, which places this source at the most luminous end of the radio luminosity function at this epoch (Saxena et al. 2017). For comparison, TNJ0924 has a K -corrected radio luminosity of $\log L_{1.4 \text{ GHz}} = 29.3 \text{ W Hz}^{-1}$ using a spectral index of $\alpha = -1.6$ (van Breugel et al. 1999). TGSS1530 is close to an order of magnitude fainter than TNJ0924–2201 at 1.4 GHz, but remains by far the brightest radio source observed this close to the end of the epoch of reionisation.

The deconvolved angular size determined by Saxena et al. (2018) at 1.4 GHz for TGSS1530, which remains unresolved, is 0.6 arcseconds, which translates to a linear size of 3.5 kpc. This size is smaller than the size of TNJ0924 (van Breugel et al. 1999) and in line with predictions at $z \sim 6$ from Saxena et al. (2017), as radio galaxies in the early Universe are expected to be young and very compact (Blundell et al. 1999). In Table 4 we compare the radio properties of TGSS1530 with all currently known radio galaxies at $z > 4$. This was done by querying the TGSS ADR1 catalog to determine flux densities for all $z > 4$ radio galaxies at 150 MHz, which were then used to calculate radio powers using the standard K -corrections. We find that TGSS1530 is comparable to many of the $z > 4$ radio galaxies when looking at radio properties alone.

TGSS1530 has a spectral index of $\alpha_{1.4 \text{ GHz}}^{150 \text{ MHz}} = -1.4$, which is ultra-steep but flatter than TNJ0924 at $z = 5.2$, which was selected because of its spectral index of $\alpha_{1.4 \text{ GHz}}^{365 \text{ MHz}} = -1.6$. Interestingly, at lower radio frequencies the spectral index of TNJ0924 appears to flatten dramatically. The 150 MHz flux density measured in TGSS (Intema et al. 2017) for TNJ0924 is $760 \pm 76 \text{ mJy}$, giving a low frequency spectral index $\alpha_{365 \text{ MHz}}^{150 \text{ MHz}} = -0.16$. If the spectral index were

Table 3. Comparison of Ly α emission line properties of TGSS1530 reported in this paper with typical radio galaxies at $z = 5.19$ and $z = 4.88$, and the much fainter radio galaxy at $z = 4.42$ (all marked as RG), in addition to several confirmed LAEs at $z \approx 5.7$ from the literature.

Name	z	$F_{Ly\alpha}$ ($\times 10^{-17}$ erg s $^{-1}$ cm $^{-2}$)	$L_{Ly\alpha}$ ($\times 10^{42}$ erg s $^{-1}$)	FWHM $_{Ly\alpha}$ (km s $^{-1}$)	Reference
TGSS1530	5.72	1.6	5.7	370	This work
TNJ0924 (RG)	5.19	3.4	9.6	1500	(van Breugel et al. 1999)
J163912.11+405236.5 (RG)	4.88	18.5	47.0	1040	(Jarvis et al. 2009)
VLA J123642+621331 (RG)	4.42	0.6	2.0	420	(Waddington et al. 1999)
LALA J142546.76+352036.3	5.75	1.6	6.7	360	(Rhoads et al. 2003)
S11 5236	5.72	14.9	9.1	200	(Lidman et al. 2012)
SDF J132344.8+272427	5.72	1.1	3.7	366	(Kashikawa et al. 2011)
HSC J232558+002557	5.70	3.6	12.6	373	(Shibuya et al. 2018)
SR6	5.67	7.6	25.0	236	(Matthee et al. 2017)

Table 4. A comparison of the radio properties of TGSS1530 with other known radio galaxies at $z > 4$. Flux densities at 150 MHz are measured from the TGSS ADR1 catalog.

Name	z	S_{150} (mJy)	$\log L_{150}$ (W Hz $^{-1}$)	Size (kpc)	Reference
TGSS1530	5.72	170	29.11	3.5	This work
TN J0924–2201	5.19	760	29.57	7.4	(van Breugel et al. 1999)
J163912.11+405236.5	4.88	103	28.21	–	(Jarvis et al. 2009)
RC J0311+0507	4.51	5981	30.31	21.1	(Parijskij et al. 2014)
VLA J123642+621331	4.42	undetected	–	–	(Waddington et al. 1999)
6C 0140+326	4.41	860	29.44	17.3	(Rawlings et al. 1996)
8C 1435+63	4.25	8070	30.37	21.1	(Lacy et al. 1994)
TN J1123–2154	4.11	512	29.14	5.5	(Reuland et al. 2004)
TN J1338–1942	4.10	1213	29.51	37.8	(Reuland et al. 2004)

to be calculated only using the flux densities at frequencies of 150 MHz and 1.4 GHz, the inferred spectral index would be $\alpha_{1.4\text{ GHz}}^{150\text{ MHz}} = -1.06$, making it not strictly ultra-steep ($\alpha < -1.3$). This implies that in a search for ultra-steep spectrum radio sources using data at 150 MHz and 1.4 GHz, such as Saxena et al. (2018), TNJ0924 would be missed entirely.

Spectral flattening or even a turnover at low radio frequencies is expected in radio galaxies at increasingly higher redshifts due to: a) Inverse Compton (IC) losses due to the denser cosmic microwave background that affect the higher frequencies and result in a steeper high frequency spectral index, and b) free-free or synchrotron self absorption due to the compact sizes of radio sources at high redshifts that can lead to a turnover in the low frequency spectrum (Callingham et al. 2017). Saxena et al. (2018) have reported evidence of flattening of the low-frequency spectral index in candidate HzRGs and observations at intermediate radio wavelengths for sources like TGSS1530 are essential to measure spectral flattening and constrain various energy loss mechanisms that dominate the environments of radio galaxies in the early Universe. Additionally, search techniques for radio galaxies at even higher redshifts could be refined by possibly using radio colours instead of a simple ultra-steep spectral index selection. The LOFAR Two Metre Sky Survey (Shimwell et al. 2017, Shimwell et al. in prep) will eventually provide in-band spectral indices at 150 MHz and could potentially be used to identify HzRG candidates more efficiently.

We also draw attention towards the radio galaxy J163912.11+405236.5 at $z = 4.88$ (Jarvis et al. 2009), that

has a spectral index of $\alpha_{1.4\text{ GHz}}^{325\text{ MHz}} = 0.75$ and is not an ultra-steep spectrum radio source. Interestingly, there is evidence of spectral flattening at lower frequencies with a 150 MHz flux density of 103.5 mJy, giving a spectral index $\alpha_{325\text{ MHz}}^{150\text{ MHz}} = -0.56$, which is flatter than that at higher frequencies. This source was targeted for spectroscopic follow-up owing to the faintness of its host galaxy at 3.6 μm . The very faint radio galaxy VLA J123642+621331 at $z = 4.42$ (Waddington et al. 1999) is also not an ultra-steep spectrum source ($\alpha = 0.94$) and is too faint to be detected in TGSS ADR1. This source was also selected based on its optical and infrared faintness, suggesting that a considerable fraction of HzRGs may not be ultra-steep at all and therefore, be missed in samples constructed using the ultra-steep spectrum selection technique.

Indeed Ker et al. (2012) have shown that selecting infrared-faint radio sources (IFRS) could be more efficient at isolating HzRGs from large samples when compared to radio selection alone. However, the caveat is that deep infrared photometry over large sky areas is required to effectively implement such a selection, which can be expensive. The recently concluded UKIRT Hemisphere Survey (UHS; Dye et al. 2018) has the potential to be extremely useful in the identification of promising HzRG candidates in the Northern Hemisphere, particularly from the LOFAR surveys (Shimwell et al. 2017, Shimwell et al. in prep).

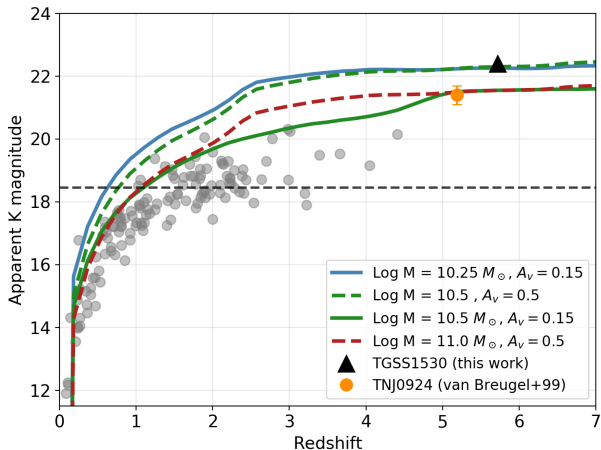


Figure 7. The ‘ $K-z$ ’ diagram for radio galaxies, showing stellar mass limits derived from stellar population synthesis modelling for TGSS1530 (black triangle). The K -band 3σ limit gives $M_{\text{stars}} < 10^{10.25} M_{\odot}$ for $A_v = 0.15$ mag, and $M_{\text{stars}} < 10^{10.5}$ for $A_v = 0.5$ mag. Also shown are K -band magnitudes and redshifts for known radio galaxies in the literature (grey points; see text), with TNJ0924 at $z = 5.2$ (orange circle). The K -band limits for TGSS1530 further help exclude lower redshift measurements from incorrect line identification.

5.3 Stellar mass limits

The non-detection of the host galaxy down to 3σ depths in the K band image from our LBT observations can be used to set limits on the stellar mass for TGSS1530 using simple stellar population synthesis modelling. To do this, we make use of the PYTHON package SMPY¹ (Duncan & Conzelice 2015), which is designed for building composite stellar populations in an easy and flexible manner, allowing for synthetic photometry to be produced for single or large suites of models. To build stellar populations, we use the Bruzual & Charlot (2003) model with a Chabrier (2003) initial mass function (IMF) and solar metallicity (Willott et al. 2003), a formation redshift $z_f = 25$ and assume a maximally old stellar population that has been forming stars at a constant rate (Lacy et al. 2000). We follow the Calzetti et al. (2000) law for dust attenuation and use values of $A_v = 0.15$ (moderate extinction) and 0.5 mag (dusty), which are commonly seen in massive galaxies at $5 < z < 6$ (McLure et al. 2006). The synthetic photometry is produced for different stellar masses, which we then convolve with the K band filter to calculate apparent K magnitudes over a redshift range 0–7.

The K magnitude limit for TGSS1530 fits well with a stellar mass limit of $M_{\text{stars}} < \sim 10^{10.25} M_{\odot}$ for $A_v = 0.15$ mag, and $M_{\text{stars}} < \sim 10^{10.5}$ for $A_v = 0.5$ mag. We note here that thanks to the excellent seeing for K -band observations (0.6–0.8 arcseconds), and since at $z \sim 6$ the host galaxy is expected to be small, any aperture correction is only expected to be at the level of a few tenths of a magnitude at most, or 0.1–0.2 in the logarithmic stellar mass, which is smaller than the uncertainty from dust extinction corrections.

¹ <https://github.com/dunkenj/smpy>

We find that the stellar mass limits we infer are in agreement with the J band 3σ limit from LBT. The photometry predicted by the models in the optical bands from PS1 (g, r, i, z, y) is also consistent with the non-detections that we report. This stellar mass limit places TGSS1530 towards the $> M^*$ end of the galaxy stellar mass function at $z \sim 6$ (see Duncan et al. 2014, for example). For comparison, we show the apparent K band magnitudes of other radio galaxies in the literature, taken from the 3CRR, 6CE, 6C* and 7C–I/II/III samples (Willott et al. 2003), in Figure 7. Also shown is the K magnitude for TN J09224–2201 at $z = 5.2$ (van Breugel et al. 1999), which is best fit with a stellar mass of $10^{10.5} M_{\odot}$ for $A_v = 0.15$ mag and $10^{11} M_{\odot}$ for $A_v = 0.5$ mag.

We also show the K -band magnitude limit for the UKIDSS LAS as a dashed black line in Figure 7. TGSS1530 was initially selected due to its non-detection in LAS. However, these magnitude limits alone were not sufficient to constrain the very high redshift nature of the host galaxy. With deeper LBT observations in K band, we show that TGSS1530 follows the trend in the $K-z$ plot for radio galaxies. It is also clear that a low redshift solution that would arise if the detected emission line in Section 4 is not Lyman alpha (for example, $z \approx 1.2$ if the line is [O II]) would be hard to explain using galaxy evolution models with the inputs and assumptions outlined above and those generally used to model radio galaxy spectra (Overzier et al. 2009).

6 CONCLUSIONS

In this paper we have presented the discovery of the highest redshift radio galaxy, TGSS1530, at $z = 5.72$. The galaxy was initially selected at 150 MHz from TGSS (Saxena et al. 2018) and was assigned a high priority for spectroscopic follow-up owing to its compact morphology and faintness at optical and near-infrared wavelengths. The conclusions of this study are listed below:

(i) Long-slit spectroscopy centered at the radio position of the source revealed an emission line at 8170 Å, which we identify as Lyman alpha at $z = 5.720$. We rule out alternative line IDs owing to the absence of other optical/UV lines in the spectrum, the asymmetrical nature of the emission line characteristic of Lyman alpha at high redshifts that we quantify using the skewness parameter and the high observed equivalent width of the emission line.

(ii) Deep J and K band imaging using the Large Binocular Telescope led to no significant detection of the host galaxy down to 3σ limits of $K > 22.4$ and $J > 24.4$. The limits in K can be used as an additional constraint on the redshift, owing to the relation that exists between K band magnitude and redshift of radio galaxies. The magnitude limit is consistent with $z > 5$, practically ruling out a redshift of $z \approx 1.2$ that would be expected if the emission line were an unresolved [O II] $\lambda\lambda 3726, 3729$ doublet, which is the most likely alternative line identification.

(iii) The emission line is best fitted with a skewed Gaussian, giving an integrated line flux of $F_{\text{Ly}\alpha} = 1.6 \times 10^{-17}$ erg s⁻¹ cm⁻², a Ly α luminosity of 5.7×10^{42} erg s⁻¹, an equivalent width of $\text{EW} > 40$ Å and a FWHM of 370 km s⁻¹. These values are more consistent with those observed in non-radio

Lyman alpha emitting galaxies at this redshift and much lower than those corresponding to typical radio galaxies at $z > 4$.

(iv) The radio luminosity calculated at 150 MHz is $\log L_{150} = 29.1 \text{ W Hz}^{-1}$, which places it at the most luminous end of the radio luminosity function at this epoch. The deconvolved angular size is 3.5 kpc, which is in line with the compact morphologies expected at high redshifts. We find that the radio properties of TGSS1530 are comparable to other known radio galaxies at $z > 4$. A joint study of the Ly α halo and the radio size of this source may provide one of the earliest constraints on the effects of radio-mode feedback.

(v) We use the K band limit to put constraints on the stellar mass estimate using simple stellar population synthesis models. Assuming a constant star formation history and a maximally old stellar population, we derive a stellar mass limit of $M_{\text{stars}} < \sim 10^{10.25} M_{\odot}$ for $A_V = 0.15$ mag, and $M_{\text{stars}} < \sim 10^{10.5}$ for $A_V = 0.5$ mag. Deeper observations are needed to further constrain the underlying stellar population in TGSS1530.

An effective application of deep radio surveys covering very large areas on the sky has been demonstrated by this discovery of the first radio galaxy at a record distance after almost 20 years. With the more sensitive, large area surveys currently underway with LOFAR (LoTSS; Shimwell et al. in prep), there is potential to push searches for bright radio galaxies to even higher redshifts. Discovery of even a single bright radio galaxy at $z > 6$ would open up new ways to study the epoch of reionisation in unparalleled detail, through searches for the 21cm absorption features left behind by the neutral hydrogen that pervaded the Universe at high redshifts.

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REFERENCES

- Afonso J., et al., 2011, *ApJ*, **743**, 122
 Alam S., et al., 2015, *ApJS*, **219**, 12
 Astropy Collaboration et al., 2013, *A&A*, **558**, A33
 Best P. N., et al., 1998, *MNRAS*, **301**, L15
 Blundell K. M., Rawlings S., Willott C. J., 1999, *AJ*, **117**, 677
 Bradley L., et al., 2017, *astropy/photutils*: v0.4, doi:10.5281/zenodo.1039309, <https://doi.org/10.5281/zenodo.1039309>
 Bridge J. S., et al., 2015, *ApJ*, **799**, 205
 Bruzual G., Charlot S., 2003, *MNRAS*, **344**, 1000
 Callingham J. R., et al., 2017, *ApJ*, **836**, 174
 Calzetti D., Armus L., Bohlin R. C., Kinney A. L., Koornneef J., Storchi-Bergmann T., 2000, *ApJ*, **533**, 682
 Carilli C. L., Harris D. E., Pentericci L., Röttgering H. J. A., Miley G. K., Kurk J. D., van Breugel W., 2002a, *ApJ*, **567**, 781
 Carilli C. L., Gnedin N. Y., Owen F., 2002b, *ApJ*, **577**, 22
 Chabrier G., 2003, *PASP*, **115**, 763
 Chambers K. C., et al., 2016, preprint, ([arXiv:1612.05560](https://arxiv.org/abs/1612.05560))
 Ciardi B., et al., 2015, *MNRAS*, **453**, 101
 De Barros S., et al., 2017, *A&A*, **608**, A123
 De Breuck C., van Breugel W., Minniti D., Miley G., Röttgering H., Stanford S. A., Carilli C., 1999, *A&A*, **352**, L51
 De Breuck C., van Breugel W., Röttgering H. J. A., Miley G., 2000, *A&AS*, **143**, 303
 De Breuck C., et al., 2010, *ApJ*, **725**, 36
 Duncan K., Conzelmann C. J., 2015, *MNRAS*, **451**, 2030
 Duncan K., et al., 2014, *MNRAS*, **444**, 2960
 Dunlop J. S., Peacock J. A., 1990, *MNRAS*, **247**, 19
 Dye S., et al., 2018, *MNRAS*, **473**, 5113
 Ewall-Wice A., Dillon J. S., Mesinger A., Hewitt J., 2014, *MNRAS*, **441**, 2476
 Furlanetto S. R., Loeb A., 2002, *ApJ*, **579**, 1
 Hatch N. A., et al., 2011, *MNRAS*, **410**, 1537
 Hunter J. D., 2007, *Computing In Science & Engineering*, **9**, 90
 Intema H. T., Jagannathan P., Mooley K. P., Frail D. A., 2017, *A&A*, **598**, A78
 Ishwara-Chandra C. H., Sirothia S. K., Wadadekar Y., Pal S., Windhorst R., 2010, *MNRAS*, **405**, 436
 Jarvis M. J., Rawlings S., Eales S., Blundell K. M., Bunker A. J., Croft S., McLure R. J., Willott C. J., 2001, *MNRAS*, **326**, 1585
 Jarvis M. J., Teimourian H., Simpson C., Smith D. J. B., Rawlings S., Bonfield D., 2009, *MNRAS*, **398**, L83
 Kalfountzou E., Jarvis M. J., Bonfield D. G., Hardcastle M. J., 2012, *MNRAS*, **427**, 2401
 Kashikawa N., et al., 2006, *ApJ*, **648**, 7
 Kashikawa N., et al., 2011, *ApJ*, **734**, 119
 Ker L. M., Best P. N., Rigby E. E., Röttgering H. J. A., Gendre M. A., 2012, *MNRAS*, **420**, 2644
 Klammer I. J., Ekers R. D., Sadler E. M., Weiss A., Hunstead R. W., De Breuck C., 2005, *ApJ*, **621**, L1

- Kurk J. D., Cimatti A., di Serego Alighieri S., Vernet J., Daddi E., Ferrara A., Ciardi B., 2004, *A&A*, **422**, L13
- Lacy M., et al., 1994, *MNRAS*, **271**, 504
- Lacy M., Bunker A. J., Ridgway S. E., 2000, *AJ*, **120**, 68
- Lawrence A., et al., 2007, *MNRAS*, **379**, 1599
- Lidman C., Hayes M., Jones D. H., Schaerer D., Westra E., Tapken C., Meisenheimer K., Verhamme A., 2012, *MNRAS*, **420**, 1946
- Lilly S. J., Longair M. S., 1984, *MNRAS*, **211**, 833
- Mack K. J., Wyithe J. S. B., 2012, *MNRAS*, **425**, 2988
- Matthee J., Sobral D., Darvish B., Santos S., Mobasher B., Paulino-Afonso A., Röttgering H., Alegre L., 2017, *MNRAS*, **472**, 772
- McLure R. J., et al., 2006, *MNRAS*, **372**, 357
- Miley G., De Breuck C., 2008, *A&ARv*, **15**, 67
- Miley G. K., et al., 2004, *Nature*, **427**, 47
- Orsi Á. A., Fanidakis N., Lacey C. G., Baugh C. M., 2016, *MNRAS*, **456**, 3827
- Ouchi M., et al., 2008, *ApJS*, **176**, 301
- Overzier R. A., et al., 2009, *ApJ*, **704**, 548
- Parijskij Y. N., et al., 2014, *MNRAS*, **439**, 2314
- Pentericci L., et al., 2000, *A&A*, **361**, L25
- Pérez F., Granger B. E., 2007, *Computing in Science and Engineering*, **9**, 21
- Rawlings S., Lacy M., Blundell K. M., Eales S. A., Bunker A. J., Garrington S. T., 1996, *Nature*, **383**, 502
- Reuland M., Röttgering H., van Breugel W., De Breuck C., 2004, *MNRAS*, **353**, 377
- Rhoads J. E., et al., 2003, *AJ*, **125**, 1006
- Rigby E. E., Best P. N., Brookes M. H., Peacock J. A., Dunlop J. S., Röttgering H. J. A., Wall J. V., Ker L., 2011, *MNRAS*, **416**, 1900
- Rigby E. E., Argyle J., Best P. N., Rosario D., Röttgering H. J. A., 2015, *A&A*, **581**, A96
- Robitaille T., Bressert E., 2012, APLpy: Astronomical Plotting Library in Python, Astrophysics Source Code Library (ascl:1208.017)
- Rocca-Volmerange B., Le Borgne D., De Breuck C., Fioc M., Moy E., 2004, *A&A*, **415**, 931
- Röttgering H. J. A., Lacy M., Miley G. K., Chambers K. C., Saunders R., 1994, *A&AS*, **108**
- Röttgering H., Daddi E., Overzier R., Wilman R., 2003, *New Astron. Rev.*, **47**, 309
- Sanders R. L., et al., 2016, *ApJ*, **816**, 23
- Saxena A., Röttgering H. J. A., Rigby E. E., 2017, *MNRAS*, **469**, 4083
- Saxena A., et al., 2018, *MNRAS*,
- Seifert W., et al., 2003, in Iye M., Moorwood A. F. M., eds, Proc. SPIE Vol. 4841, Instrument Design and Performance for Optical/Infrared Ground-based Telescopes. pp 962–973, doi:10.1117/12.459494
- Shibuya T., et al., 2018, *PASJ*, **70**, S15
- Shimakawa R., et al., 2015, *MNRAS*, **451**, 1284
- Shimwell T. W., et al., 2017, *A&A*, **598**, A104
- Spinrad H., Dey A., Graham J. R., 1995, *ApJ*, **438**, L51
- Steidel C. C., et al., 2014, *ApJ*, **795**, 165
- Taylor M. B., 2005, in Shopbell P., Britton M., Ebert R., eds, Astronomical Society of the Pacific Conference Series Vol. 347, Astronomical Data Analysis Software and Systems XIV. p. 29
- Venemans B. P., et al., 2002, *ApJ*, **569**, L11
- Waddington I., Windhorst R. A., Cohen S. H., Partridge R. B., Spinrad H., Stern D., 1999, *ApJ*, **526**, L77
- Willott C. J., Rawlings S., Blundell K. M., Lacy M., Eales S. A., 2001, *MNRAS*, **322**, 536
- Willott C. J., Rawlings S., Jarvis M. J., Blundell K. M., 2003, *MNRAS*, **339**, 173
- Wright E. L., et al., 2010, *AJ*, **140**, 1868
- Xu Y., Chen X., Fan Z., Trac H., Cen R., 2009, *ApJ*, **704**, 1396
- van Breugel W., De Breuck C., Stanford S. A., Stern D., Röttgering H., Miley G., 1999, *ApJ*, **518**, L61

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