The discovery of a type-II quasar at $z = 1.65$ with integral-field spectroscopy*

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ABSTRACT

In this letter we report the serendipitous discovery of a genuine type-II quasar at $z = 1.65$ using integral-field data from VIMOS on the VLT. This is the first discovery of a type-II quasar at $z > 1$ from optical data alone. J094531-242831, hereafter J0945-2428, exhibits strong narrow ($v < 1500$ km s^{-1}) emission lines, has a resolved host galaxy, and is undetected to a radio flux-density limit of $S_{\rm 5GHz} = 0.15$ mJy (3σ). All of these lead us to believe that J0945-2428 is a bona fide type-II quasar.

The luminosity of the narrow-emission lines in this object suggest that the intrinsic power of the central engine is similar to that found in powerful radio galaxies, indicative of similarly large supermassive black hole of $\sim 3 \times 10^8$ M$_\odot$ (assuming that it is accreting at its Eddington limit). However, from near-infrared imaging observations we find that the old stellar population in the host galaxy has a luminosity of $\sim 0.2\ L^\star$, mildly inconsistent with the correlation between black-hole mass and bulge luminosity found locally, although the uncertainty in the black-hole mass estimate is large.

This discovery highlights the power that integral-field units have in discovering hidden populations of objects, particularly the sought after type-II quasars which are invoked to explain the hard X-ray background. As such, future large integral-field surveys could open up a new window on the obscured accretion activity in the Universe.

Key words: galaxies:active – quasars:emission lines – quasars:individual(J094531-242831)

1 INTRODUCTION

Under the unification picture of active galactic nuclei (AGN), radio galaxies and radio-loud quasars are believed to be the same type of object. Under this unification scheme only viewing angle dictates whether we see the object optically as a quasar with broad permitted lines in emission and an unresolved optical core, or as a radio galaxy with only narrow emission lines and where the host galaxy is resolved (see e.g. Urry & Padovani 1995).

Applying the same reasoning to radio-quiet quasars, which outnumber their radio-loud counterparts by a factor of $\sim 10 - 100$ (e.g. Goldschmidt et al. 1999), there should be a population of radio-quiet quasars which are obscured in the same way as radio galaxies such that their quasar nuclei shine along the plane of the sky, the so-called type-II quasars. However, such sources are extremely difficult to detect, because they would appear as normal elliptical galaxies in optical or near-infrared images and only spectroscopy would detect the strong narrow-emission lines.

From an X-ray perspective the hypothesis that there must be a population of type-II quasars, in which the direct light from the quasar is obscured and only narrow emission lines are observed, is a cornerstone assumption for models of the hard-X-ray background (XRB; e.g. Wilman & Fabian 1999; Wilman, Fabian & Nulsen 2000). This requirement for type-II quasars by models of the XRB fits in well with the orientation based arguments for radio-loud objects.

With the advent of the latest generation of X-ray satellites (CHANDRA and XMM-Newton), the majority of the XRB in the Chandra band (< 8 keV) has been resolved (e.g. Alexander et al. 2003). The bulk of which is produced by Seyferts and quasars with moderate obscuration ($N_{\rm H} < 2 \times 10^{23}$ cm^{-2}), where the Seyferts evolve quite rapidly to $z = 0.8$ and the quasars evolve somewhat more

slowly. But of this population, only a handful are bona fide type-II quasars (e.g. Gandhi et al. 2004).

The situation at harder energies is quite different. The majority of the hard sources lie at the faint end of the flux distribution (e.g. Fig. 2 in Giacconi et al. 2001) and only 50 per cent of the XRB above 7 keV is resolved (e.g. Worsley et al. 2004). The unresolved flux has the spectrum of a highly obscured AGN, suggesting that the range of column density at $z \sim 1$ is similar to that locally, implying that there is a bias towards highly obscured, Compton-thick objects. This essentially means that there may be many obscured AGN which have yet to be discovered in the large, well-studied fields in the literature.

In addition to the high obscuring column densities causing the hardening of the X-ray spectra there are other reasons why some quasars may be obscured and others not. These include factors such as intrinsic luminosity (e.g. Simpson, Rawlings & Lacy 1999; Ueda et al. 2003; Hasinger et al. 2004) and the rate at which the black-hole accretes mass (e.g. Fabian 1999), which may be needed to derive a complete unification model for active galactic nuclei (AGN). This is borne out by the diversity of the hard-X-ray sources when observed in the optical and near-infrared (e.g. Barger et al. 2002). From these studies it is apparent that the frequency and distribution of gas and dust plays a major rôle in determining how we see these quasars.

Thus, any alternative method in which these obscured quasars may be discovered would be extremely important.

In this letter we report the serendipitous discovery of a genuine type-II quasar from large-volume integral-field observations with VIMOS on the VLT.

In section 2 we briefly summarise the observing strategy and data reduction procedure and in section 3 we provide detailed information of the type-II quasar including host galaxy properties and an estimate of its black-hole mass. In section 4 we summarise our conclusions and discuss how the discovery of this object with integral-field observations may open up a new window on the obscured AGN population. We use $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $H_\circ = 70$ km s^{-1} Mpc^{-1} throughout, unless stated otherwise.

2   OBSERVATIONS AND DATA REDUCTION

All of our observations were made on the nights of 29th April to the 2nd May 2003 with the Visible Multi-object Spectrograph integral-field unit (VIMOS-IFU) on UT3 of the very large telescope (VLT). The IFU consists of an array of 80×80 fibres coupled to microlenses. Our observations were carried out in the low-resolution mode with the LR-Blue grism giving a wavelength coverage of 3500Å-7000Å at 5.35Å per pixel. We also used the low-resolution spatial sampling which means that each fibre samples an area of 0.67 arcsec resulting in a field-of-view per exposure of 54×54 arcsec^2.

The observations were centred on the powerful radio galaxy MRC0943-242 at $z = 2.92$ (Röttgering et al. 1995). The total exposure time was 9 hours, split into 18 exposures of 30 minutes which were dithered by 10 arcsec around the central radio galaxy to enable accurate sky removal and cosmic-ray rejection. All observations were taken in seeing of < 0.8 arcsec.
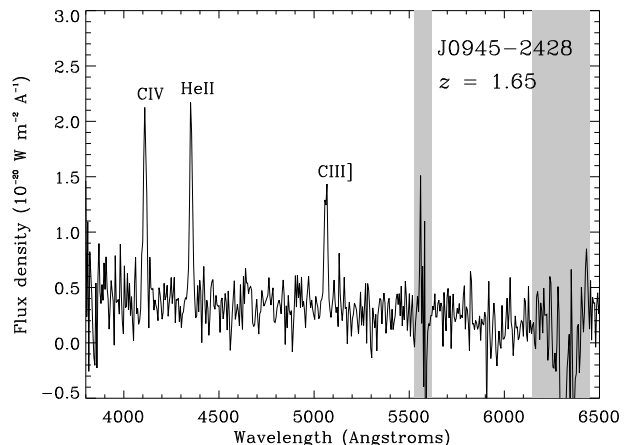
Figure 1. The 1-D spectrum of the type-II quasar, J0945-2428 at $z = 1.65$. The spectrum was extracted over the whole galaxy (seven IFU fibres). The shaded regions show the wavelengths affected by sky-line emission.
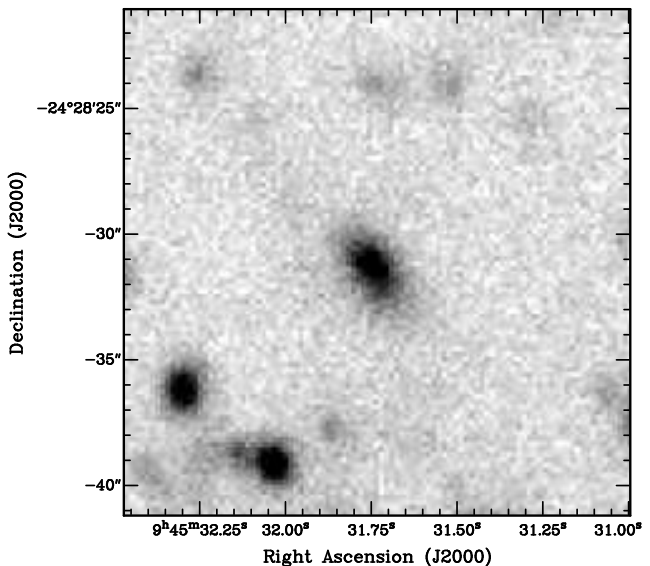
Figure 2. V-band image of J0945-2428, clearly showing that the host galaxy is resolved.

We briefly discuss the data reduction here, although a more complete description can be found in van Breukelen & Jarvis (in prep.). To reduce the data we used the VIMOS Interactive Pipeline and Graphical Interface (VIPGI) software (Scodeggio et al. 2004) which takes the raw images and performs the usual bias subtraction, flat-fielding, wavelength calibration and combining of the individual frames. For the IFU data the final dataset is combined into a datacube of two-spatial dimensions and a third spectral dimension. The spectrophotometric calibration is achieved via a script in VIPGI which provides an accurate solution for the relative flux-calibration between fibres, however, the absolute flux-calibration is unreliable. Therefore, to overcome this we used

a calibrated spectrum of the central radio galaxy MRC0943-242 and summed the fibres in our IFU data cube along the slit direction, and the V-band photometry of the type-II quasar, allowing us to bootstrap the spectrophotometry. The final flux calibration is good to ~ 20 per cent.

The final datacube was used to find emission-line objects within the volume probed with the IFU, from which we discovered the type-II quasar discussed in this letter. A detailed investigation of the number of Lyman-α emitters in the volume is deferred to a subsequent paper (van Breukelen & Jarvis in prep.).

3 RESULTS

3.1 A bona fide type-II quasar?

Figure 1 shows the extracted 1-D spectrum of the type-II quasar discovered in our datacube at a redshift of $z = 1.65$ at $\alpha = 09^h 45^m 31.74^s$, $\delta = -24°28'31.3''$. Details of the emission-line characteristics can be found in table 1. The type-II spectrum is very similar to that of a powerful radio galaxy (see e.g. Jarvis et al. 2001a) with bright narrow ($v < 1500$ km s^{-1}) emission lines where the the CIV emission lines have luminosities of 10^{35} W$< L_{\rm CIV} < 10^{36.5}$ W. The host-galaxy morphology is also resolved in the optical bands (see figure 2), implying that the central engine is obscured along the line-of-sight, again similar to radio galaxies.

To confirm this as a genuine type-II quasar and not just a radio galaxy we determine whether the source has any powerful radio emission. We use the 5 GHz radio map of Carilli et al. (1997) of the field surrounding MRC0943-242[1]. At the position of the type-II quasar there is no detectable radio emission down to a 3σ sensitivity of $S_{\rm 5GHz} = 0.15$ mJy. Given the redshift of the type-II quasar and assuming a typical spectral index for the radio emission from the core of a radio-quiet quasar of $\alpha = 0.7$ (Kukula et al. 1998), this corresponds to a radio luminosity of $L_{\rm 5GHz} < 1.6 \times 10^{23}$ W Hz^{-1} sr^{-1}. This is a factor of 10 fainter than the traditional division between radio-loud and radio-quiet quasars (e.g. Miller, Peacock & Mead 1990). Thus, the object is radio-quiet.

Further, the emission-line ratios and equivalent widths are very similar to radio galaxies, as opposed to quasars and Seyfert II galaxies. The emission-line ratios of McCarthy (1993) show that for a radio galaxy, the typical ratio of CIV/HeII= 1.1, and HeII/CIII] $\sim$1.8, in J0945-2428 we find CIV/HeII= 1.1 and HeII/CIII]=1.3. For quasars and Seyfert II galaxies the same ratios from McCarthy (1993) are $({\rm CIV/HeII})_{\rm QSO} = 8.6$ and $({\rm CIV/HeII})_{\rm SyII} = 5.9$ and $({\rm HeII/CIII}])_{\rm QSO} = 0.26$ and $({\rm HeII/CIII}])_{\rm SyII} = 0.37$. Thus, the emission-line ratios are much more consistent with those of powerful radio galaxies than other types of AGN.

The CIV/HeII ratio in J0945-2428 is however marginally smaller than other type-II quasars discovered via their X-ray emission in the literature. Stern et al. (2002) find that CXO 52 has a CIV/HeII flux-ratio of ≈ 2 and HeII/CIII] ~ 0.8, although the CIV/HeII emission-line ratio of CDF-S 202 (Norman et al. 2002) is much higher at

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[1] We also analysed the 1.4 GHz map from the VLA archive, but this was only sensitive to ~ 0.7 mJy (3σ).

Table 2. Photometric properties of the type-II quasar. The B-band photometry was measured from a 75 minute exposure of this field with FORS2 on the VLT. The V- and I-band photometry was measured from 93 minute and 40 minute exposures respectively with LRIS on the Keck telescope.

Band	Magnitude
B	23.00 ±0.02
V	22.88 ±0.02
I	22.2 ±0.2
K	20.5 ±0.2

CIV/HeII ~ 3.5, albeit still far from the ratio of a typical quasar (e.g. Vanden Berk et al. 2001). This can possibly explained by the the fact the CIV is a resonant line and as such some of its flux may be absorbed along the line of sight, thus making it appear fainter in our low-resolution observations. Another possible effect is that carbon may deplete onto dust grains (e.g. Villar-Martín, Binette & Fosbury 1996). Both of these factors could easily reduce the CIV luminosity whereas the HeII luminosity would remain roughly constant.

The only other emission lines that we would expect in our spectrum would be OIII]λ1663 and CIII]λ2326. From our spectrum we can set a 3σ limit on the OIII]λ1663 emission line of $< 4 \times 10^{34}$ W, at least a factor of 15 fainter than the CIV line. This is again in line with observations of high-redshift radio galaxies. The CIII]λ2326 line would lie at 6164Å, and is thus very close to the atmospheric emission highlighted in Fig. 1.

3.2 The host galaxy of J0945-2428

The type-II quasar has a continuum magnitude of $V = 22.8$, which if we assume typical galaxy colours of an evolved elliptical galaxy at $z = 1.65$ of $V - K \sim 5$ (Poggianti 1997) leads to $K \sim 17.8$, typical of a radio galaxy at $z = 1.65$ (e.g. Jarvis et al. 2001b; Willott et al. 2003). However, using archival NTT-SofI data [programme ID: 70.A-0514(A)] on this field we find that the AGN has $K = 20.5 \pm 0.2$. The $K-$band light samples the old stellar population at this redshift and should therefore provide a good estimate of the stellar mass of the host, but we find that the galaxy is much fainter than the expected luminosity for a massive host galaxy. Indeed, $K = 20.5$ corresponds to $\sim 0.2\ L^\star$ at $z = 1.65$ completely at odds with the radio galaxy $K - z$ relation (e.g. Jarvis et al. 2001b).

The broad-band colours (Table 2) also show that the host galaxy is extremely blue, with $B - I = 0.8$ and $I - K = 1.7$, indicating that the host may have a large amount of ongoing star formation. Coupled with the faintness of the host in the near-infrared this suggests that the host may be undergoing its first major star-forming event and sub-millimetre observations would be able to confirm this.

There are also no obvious signs of merger activity, with the galaxy profile exhibiting a disk-like morphology with a scale-length of $r = 9.2\pm0.7$ kpc, similar to the largest Seyfert galaxies (e.g. Virani, De Robertis & VanDalfsen 2000). However, it is worth pointing out that we are sampling the UV-emitting stellar population in our V-band (where we have the best signal-to-noise ratio), and that the longer wave-

Table 1. Emission-line measurements for the type-II quasar J0945-2428. The uncertainties on the line-flux measurements are $\approx$30 per cent.

Emission line	λ (Å)	z	FWHM (km s^{-1})	Flux / 10^{-19} (W m^{-2})	$L/10^{35}$ (W)
CIVλ1549	4112	1.654	< 1376	3.5	6.3
HeIIλ1640	4355	1.655	< 1127	3.2	5.8
CIII]λ1909	5065	1.653	< 1167	2.4	4.3
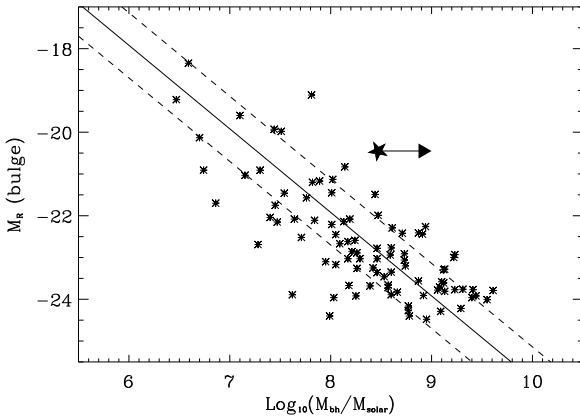
Figure 3. The position of J0945-2428 (filled star) on bulge luminosity versus black-hole mass relation. We use the back-hole mass derived from the strength of the UV emission lines as detailed in section 3.3, this is a lower limit which assumes the black hole is accreting at its Eddington limit. M_R is calculated from the fact that $K = 20.5$ corresponds to $0.2L^\star$ from the $K-$band luminosity function (Kochanek et al. 2001) and $M_R^\star = -22.2$ (Lin et al. 1996). The solid line represents the best fit relation from McLure & Dunlop (2002) for inactive and active galaxies at $z < 0.5$ and the small stars represent the objects from their data set. All points are for $\Omega_M = 1$, $\Omega_\Lambda = 0$ and $H_\circ = 50$ km s^{-1} Mpc^{-1} to allow comparison with previous work.

length data sample the old stellar population may not have such a morphology or scale-length, and further observations will be need to investigate this.

3.3   The mass of the black-hole in J0945-2428

If we use the typical line ratios for radio galaxies then we are able to estimate the strength of the [OII] emission lines and gain an estimate of the bolometric luminosity, $L_{\rm Bol}$ of the central engine. We use the relation given in Willott et al. (1999) relating $L_{\rm Bol}$ to the luminosity of the [OII]λ3727 line $L_{\rm [OII]}$, $L_{\rm Bol} = 5 \times 10^3 L_{\rm [OII]}$ W, along with the line ratios from McCarthy (1993). Thus, assuming CIV/[OII] = 1.0 means J0945-2428 has a bolometric luminosity $L_{\rm Bol} \sim 3.2 \times 10^{39}$ W. If the central engine is accreting at its Eddington limit, then this corresponds to a black-hole mass of $\sim 3 \times 10^8$ M$_\odot$.

Using the relation linking bolometric luminosity to the monochromatic luminosity at 2500Å(L_{2500}) from Elvis et al. (1994) and given the relation between X-ray luminosity at 2 keV ($L_{2\rm keV}$), and L_{2500} from Risaliti, Elvis & Gilli (2002) with an optical–X-ray spectral index of $\alpha_{OX} = 1.6$, this

provides a very rough estimate of the expected X-ray flux at 2 keV. Combining these relations shows that J0945-2428 would have an X-ray luminosity of $L_{2\rm keV} \sim 10^{37}$ W. This is also consistent with taking the typical line ratios found in radio galaxies and linking the X-ray luminosity to the Hβ luminosity (e.g. Ward et al. 1988).

These properties are typical of a powerful AGN at these redshifts and imply that it is in the regime of black-hole mass where powerful radio emission is able to be produced (e.g. McLure & Jarvis 2004). However, such a massive black hole should be hosted by a massive galaxy if the relation between black-hole mass and bulge luminosity (Magorrian et al. 1998) holds to high redshifts. From our $K-$band image we find that this is not the case, which in turn implies that the black-hole mass – bulge luminosity correlation may break down (Fig. 3) in the early Universe. Thus massive black holes may be in place before the host galaxy has fully built up. However, this is highly tentative and obviously more observations are needed of this object and other such quasars before such a statement can be made in earnest.

3.4   Obscuration toward the nucleus of J0945-2428

To estimate the amount of obscuration toward the quasar nucleus we adopt the Bolometric correction of $L_{\rm Bol} = 5.6 \times L_{2500}$ from Elvis et al. (1994), to calculate the continuum flux expected in our optical spectrum. This leads to a monochromatic luminosity at rest-frame 2500Å of $L_{2500} = 5.3 \times 10^{38}$ W. From our extracted spectrum (Fig. 1) we find a monochromatic luminosity of $L_{2500} \sim 10^{34}$ W. This leads to a visual extinction of $A_V \gtrsim 4$ mag toward the quasar nucleus, which can easily explain the lack of a nuclear point source in the $K-$band image. Again this is in line with studies of powerful radio galaxies (e.g. Simpson et al. 1999).

3.5   The space density of obscured AGN

Obviously with a single object it is very difficult to estimate the space density of obscured AGN in the high-redshift Universe. However, it is interesting to note that there are two other AGN in the volume probed by our IFU observations, the powerful radio galaxy that we targeted and a traditional broad-line quasar at $z = 1.79$ at $\alpha = 09^h 45^m 32.92^s$, $\delta = -24°29'09.1''$ (Fig. 4). Therefore, the best we can say is that obscured AGN are consistent with being as abundant as their type-I counterparts, but obviously a larger volume search with IFUs will be able to pin-down this fraction in a highly efficient and unbiased manner.
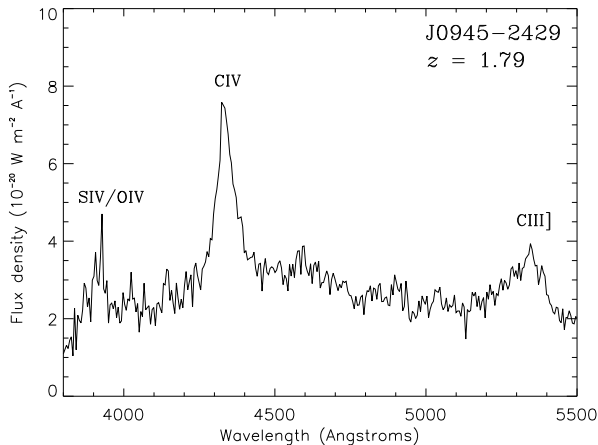
Figure 4. The 1-D spectrum of J0945-2429, the $z = 1.79$ unobscured quasar in our IFU volume. The spectrum was extracted over three IFU fibres.

4 CONCLUSIONS

We have reported the first discovery of a genuine type-II quasar from optical data alone. This was made possible by the unique capabilities of the wide-field integral-field unit VIMOS on the VLT.

J0945-2428 has narrow emission lines ($v < 1500$ km s^{-1}), a resolved host galaxy and no detectable radio emission down to a flux-density limit of $S_{5GHz} = 0.15$ mJy ($L_{5GHz} = 1.6 \times 10^{23}$ W Hz^{-1} sr^{-1}) at $z = 1.65$, indicative of a bona fide radio-quiet type-II quasar.

Using typical emission-line ratios of powerful radio galaxies and assuming that it is accreting at its Eddington limit, we show that J0945-2428 contains a supermassive black hole of mass $\sim 3 \times 10^8$ M$_\odot$. However, from deep $K-$band imaging we find that the host galaxy has a luminosity of ~ 0.2 L*, placing this type-II quasar approximately 3σ away from the relation between galaxy bulge luminosity and black-hole mass. This may be indicative of the supermassive black hole in this object being in place before the host galaxy is fully formed. This is also reinforced by the very blue colour of the host galaxy, indicative of a large amount of ongoing star formation activity. Although further observations of this source and others are needed to confirm these results.

This serendipitous discovery of an obscured quasar highlights the way in which wide-area integral-field units on large telescope could open up a unique window on the Universe. VIMOS is currently the only instrument that has the capability of large spectral coverage coupled with a ~ 1 square arcminute field of view. However, future instruments, such as the Multi-Unit Spectroscopic Explorer (MUSE; http://clio.univ-lyon1.fr/MUSE/), will expand the initial work which is taking place with VIMOS.

Furthermore, obscured AGN are not the only extragalactic sources which may be discovered with volumetric surveys. Surveys with integral-field units will discover other objects such as bare quasars with unusual optical spectra which precludes them from being identified as AGN in colour-colour diagrams, Lyman-α emitters (van Breukelen & Jarvis in prep.) and possibly objects yet to be discovered.

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