Similarity of ionized gas nebulae around unobscured and obscured quasars

Guilin Liu,† Nadia L. Zakamska1 and Jenny E. Greene2

1 Center for Astrophysical Sciences, Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St, Baltimore, MD 21218, USA
2 Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA

Accepted 2014 May 14. Received 2014 May 13; in original form 2013 December 22

ABSTRACT

Quasar feedback is suspected to play a key role in the evolution of massive galaxies, by removing or reheating gas in quasar host galaxies and thus limiting the amount of star formation. In this paper, we continue our investigation of quasar-driven winds on galaxy-wide scales. We conduct Gemini Integral Field Unit spectroscopy of a sample of luminous unobscured (type 1) quasars, to determine the morphology and kinematics of ionized gas around these objects, predominantly via observations of the [O III] λ5007 Å emission line. We find that ionized gas nebulae extend out to ~13 kpc from the quasar, that they are smooth and round, and that their kinematics are inconsistent with gas in dynamical equilibrium with the host galaxy. The observed morphological and kinematic properties are strikingly similar to those of ionized gas around obscured (type 2) quasars with matched [O III] luminosity, with marginal evidence that nebulae around unobscured quasars are slightly more compact. Therefore, in samples of obscured and unobscured quasars carefully matched in [O III] luminosity, we find support for the standard geometry-based unification model of active galactic nuclei, in that the intrinsic properties of the quasars, of their hosts and of their ionized gas appear to be very similar. Given the apparent ubiquity of extended ionized regions, we are forced to conclude that either the quasar is at least partially illuminating pre-existing gas or that both samples of quasars are seen during advanced stages of quasar feedback. In the latter case, we may be biased by our [O III]-based selection against quasars in the early ‘blow-out’ phase, for example due to dust obscuration.

Key words: galaxies: formation – galaxies: ISM – galaxies: nuclei – quasars: emission lines.

1 INTRODUCTION

The discovery of a tight relationship between the masses of black holes in nearby galaxies and the velocities and masses of their stellar populations (e.g. Magorrian et al. 1998; Gebhardt et al. 2000) strongly suggests that the active phase of black hole evolution has profound effects on the formation of massive galaxies. If the energy output of the black hole can somehow couple to the surrounding gas – for example by blowing large-scale winds – then the observed correlations can be reproduced (Hopkins et al. 2006). The physical properties of such winds, their launching mechanisms, their impact on galaxies, and their incidence in various types of active galaxies are currently the subject of intensive observational and theoretical research efforts (e.g. Croton et al. 2006; Nesvadba et al. 2008; Moe et al. 2009; Zubovas & King 2012; Wagner, Umemura & Bicknell 2013).

In the past several years, we have undertaken an observational campaign to map out the kinematics of the ionized gas around luminous obscured quasars (Zakamska et al. 2003; Reyes et al. 2008) using Magellan, Gemini and other facilities in search of signatures of quasar-driven winds (Greene et al. 2009, 2011; Greene, Zakamska & Smith 2012; Hainline et al. 2013, 2014; Liu et al. 2013a,b). In our observations, we are focusing on the most powerful quasars, where feedback effects are expected to be strongest, and we take the observational advantages provided by circumnuclear obscuration to maximize sensitivity to faint extended emission associated with quasar feedback. Our goal is to determine whether quasars can launch powerful winds via radiation pressure (Murray et al. 1995; Proga, Stone & Kallman 2000) in the most common radio-quiet mode of accretion activity, without the aid of the relativistic jets known to drive gas outflows in some objects (Nesvadba et al. 2008).

In 2010 December, we conducted a Gemini-North Multi-Object Spectrograph (GMOS-N) Integral Field Unit (IFU) campaign which targeted a sample of 11 obscured ‘type 2’ luminous radio-quiet quasars at z ~ 0.5. In the papers describing our results (Liu et al. ...
2013a,b), we present the analysis of the extents, morphologies and gas kinematics of the narrow emission line regions of these objects, predominantly via the [O iii] λ5007 Å line (hereafter [O iii]). We detect extended emission line nebulae in every case, extending out to 15–40 kpc from the centre of the galaxy. Compared to ionized gas nebulae around radio-loud objects at low and high redshifts, our targets show morphologies that are more regular and smooth and less elongated (Liu et al. 2013a). The nebulae in our sample display well-organized velocity fields with velocity dispersions ~10^3 km s^{-1} over the entire face of the nebulae (Liu et al. 2013b). The most likely explanation for these observations is that the quasars in our sample have ionized gas winds with large covering factors and propagation velocities (~800 km s^{-1}) that likely exceed the escape velocities of their host galaxies; we estimate the kinetic energies of the outflowing ionized gas to be well in excess of 10^{46} erg s^{-1}. Our analysis demonstrates that obscured radio-quiet quasars can drive gas outflows of similar scale, luminosity and velocity as those seen in some powerful radio galaxies (Nesvadba et al. 2008).

The standard geometric unification model postulates that type 1 and type 2 quasars differ only by the orientation of the observer’s line of sight relative to distribution of the obscuring material (Antonucci 1993). In this case, the observer’s line of sight is blocked in type 2 objects, but photons from the quasar can escape along other directions, scatter off the interstellar material in the host galaxy and reach the observer. We find strong support for this picture in luminous type 2 quasars: both extended scattering regions (Zakamska et al. 2006) and scattered broad emission lines (Zakamska et al. 2005) are seen in the data. Thus, the objects in our sample are unambiguously seen as type 1 quasars along the unobscured directions. If type 1 and type 2 objects differ only by the orientation of the circumnuclear obscuration relative to the observer’s line of sight, then we expect to see very similar distributions of ionized gas around quasars of both types (modulo perhaps some minor differences if the ionized gas is distributed in bicones which would be viewed closer to or farther from the axis in type 1 and type 2 sources, respectively).

However, there may be more to the story. Theoretical models of galaxy formation have long utilized evolutionary scenarios in which galaxy mergers induce both star formation and nuclear activity. This active phase, characterized by largely obscured (type 2) accretion and star formation, is then terminated by a quasar-driven wind which clears out the surrounding gas and triggers a transition of the active black hole into an unobscured (type 1) quasar phase (e.g. Sanders & Mirabel 1996; Hopkins et al. 2006; Hopkins & Hernquist 2010). A variety of observational studies support a transition of this type, finding that type 2 quasar host galaxies exhibit more energetically significant star formation than those of type 1s (e.g. Lacy et al. 2007; Zakamska et al. 2008). In this evolutionary paradigm of quasar obscuration, one might expect to find more prominent winds in the type 2 objects (more characteristic of the ‘blow-out’ phase) than in the type 1s.

In this paper, we present an observational test of evolutionary models and geometric models of quasar obscuration. We investigate whether the properties of the ionized gas nebulae around luminous quasars are associated in any way with the circumnuclear obscuration that determines the optical type of the active nucleus. We select a sample of 12 type 1 quasars that are well matched in redshift and [O iii] luminosity to our previously studied sample of luminous obscured quasars (Liu et al. 2013a,b) and conduct observations of the ionized gas around these objects in a manner identical to the one we employed in our previous work. In Section 2, we describe sample selection, observations, data reduction and calibrations. In Section 3, we present maps of the ionized gas emission, and in Section 4, we compare properties of nebulae in obscured and unobscured quasars. In Section 5, we discuss the implications of our findings, discuss morphologies of the nebulae, and we summarize in Section 6. As in Liu et al. (2013a,b), we adopt an h = 0.71, Ωm = 0.27, ΩΛ = 0.73 cosmology throughout this paper; objects are identified as SDSS Jhmmss.s+ddmmss.s in the tables and are shortened to SDSS Jhmm+dmmm elsewhere; and the rest-frame wavelengths of the emission lines are given in air.

2 DATA AND MEASUREMENTS

2.1 Sample selection

In our previous Gemini IFU campaign completed in 2010 December, we mapped ionized gas nebulae around 11 type 2 radio-quiet quasars selected from (Reyes et al. 2008). These objects were selected to be as luminous as possible in the [O iii] line (L_{[O III]} ≥ 10^{43.5} erg s^{-1}, corresponding to estimated intrinsic luminosities of the active nucleus of M_B < −26.2 mag) while being at low enough redshift (0.4 < z < 0.6) to maximize the spatial information. In this work, we study a sample of 12 type 1 radio-quiet/weak quasars selected from (Shen et al. 2011) according to the following criteria:

(i) We match the [O iii] λ5007 Å line luminosities of the selected unobscured quasars to the 11 obscured quasars we studied in Liu et al. (2013a,b). The selected quasars have [O iii] line luminosities L_{[OIII]} > 10^{42.9} erg s^{-1} (Fig. 1).
(ii) As we do for Liu et al. (2013a,b), we select the objects at redshifts z = 0.4–0.6 (Fig. 1).
(iii) All quasars are selected to be radio-quiet/weak. Conservatively, we require their radio flux at 1.4 GHz from FIRST and NVSS (Becker et al. 1995; White et al. 1997; Condon et al. 1998) to be f_{<1.4GHz} < 10 mJy, a criterion identical to the one applied for the obscured sample.
(iv) We focus on objects with high [O iii] equivalent widths, which also tend to have low Fe II luminosity (Boroson & Green 1992). The reasons are twofold. First, the relatively low levels of continuum and Fe II emission reduce contamination from the bright point-like quasar making it easier to perform measurements of faint extended emission. Secondly, we thus maximize our chances of resolving the extended [O iii] emission in light of the recent suggestion that the most extended and luminous ionized gas nebulae are found around quasars with weak emission from Fe II lines and complexes (Matsuoka 2012). As a result, considerable Fe II emission only exists in two of our targets (SDSS J0304+0022 and SDSS J0924+0642). In general, [O iii] selection results in a bias towards objects with
Figure 2. Spectra of the 12 proposed targets in their respective rest frames, from Data Release 8 of the SDSS. We concentrate on quasars that have high equivalent widths of [O III] and low equivalent width of Fe II (Boroson & Green 1992). The marked emission lines are: (a) [O III] 3727 Å; (b) [Ne III] 3869 Å; (c) [Ne II] 3871 Å; (d) Hδ 4102 Å; (e) [O III] 4363 Å; (f) He II 4686 Å; (g) Hβ 4861 Å; (i) [O III] 4959 Å; (j) [O III] 5007 Å. The velocity substructures in the [O III] 5007 Å line is shown in the right-hand panels, where de-redshifting is performed using their SDSS redshifts (Table 1).

radio jets (Boroson 2002), but because we also impose a stringent limit on the radio emission, such objects are unlikely to dominate our sample. The origin of radio emission in radio-weak objects is a topic of active debate (Condon et al. 2013; Mullaney et al. 2013; Zakamska & Greene 2014). For our purposes, the important aspects of the selection are that (1) our sources are not dominated by powerful relativistic jets, and (2) the type 1 and type 2 sources are selected to have similar radio properties to enable a direct comparison.

We show the Sloan Digital Sky Survey (SDSS) spectra of our chosen targets in Fig. 2. Although all spatial information is lost, these spectra (collected within a 3 arcsec fibre) cover a much broader wavelength range than our Gemini data.

2.2 Observations and data reduction
We observed 12 radio-quiet/weak unobscured quasars (Table 1) with GMOS-N IFU (Allington-Smith et al. 2002) between 2012 September and 2013 January (programme ID: GN-2012B-Q-29, PI: G. Liu) to determine the spatial distribution of their emission. We use the two-slit mode that covers a 5 arcsec × 7 arcsec field of view.
| Object name   | $f_{1.4\,GHz}$ | $M_B$ | $R$ | $z$ | $PA$ | $\exp$ | $\lambda_c$ | Seeing | $\log L_{[\text{OIII}]}$ | $\eta$ | $\nu_L/eV$ at 8 $\mu$m |
|--------------|----------------|-------|-----|-----|------|--------|-------------|--------|------------------------|-------|------------------------|
| SDSS J023342.57–074325.8 | $<1.1$ | $-24.8$ | $<0.4$ | $0.4538$ | $300$ | $1620 \times 2$ | $800$ | $0.42$ | $43.13$ | $2.94 \pm 0.03$ | $45.05$ |
| SDSS J030422.39+002231.8 | $<0.8$ | $-26.9$ | $<0.3$ | $0.6385$ | $0$ | $1620 \times 2$ | $800$ | $0.47$ | $42.82$ | $3.89 \pm 0.37$ | $45.91$ |
| SDSS J031154.51–070741.9 | $<1.1$ | $-25.4$ | $<0.5$ | $0.6330$ | $180$ | $1620 \times 2$ | $800$ | $0.60$ | $42.94$ | $3.93 \pm 0.14$ | $45.84$ |
| SDSS J041210.17–051109.1 | $3.2$ | $-26.0$ | $0.5$ | $0.5492$ | $185$ | $1620 \times 2$ | $760$ | $0.39$ | $43.50$ | $2.58 \pm 0.07$ | $45.79$ |
| SDSS J075352.98+315341.6 | $<1.0$ | $-24.5$ | $<0.5$ | $0.4938$ | $180$ | $1620 \times 2$ | $760$ | $0.51$ | $42.62$ | $2.57 \pm 0.05$ | $44.63$ |
| SDSS J080954.38+074355.1 | $<1.0$ | $-26.6$ | $<0.0$ | $0.6527$ | $270$ | $1620 \times 2$ | $800$ | $0.48$ | $42.35$ | $3.88 \pm 0.07$ | $45.66$ |
| SDSS J084702.55–234011.0 | $<1.5$ | $-50.0$ | $<0.5$ | $0.5662$ | $270$ | $1620 \times 2$ | $760$ | $0.60$ | $42.71$ | $3.12 \pm 0.11$ | $44.98$ |
| SDSS J090002.21+345926.5 | $<1.0$ | $-25.5$ | $<0.3$ | $0.5749$ | $210$ | $1620 \times 2$ | $800$ | $0.63$ | $43.12$ | $4.22 \pm 0.07$ | $45.62$ |
| SDSS J092423.42+064250.6 | $<1.1$ | $-26.1$ | $<0.1$ | $0.5884$ | $280$ | $1620 \times 2$ | $800$ | $0.48$ | $42.95$ | $4.54 \pm 0.22$ | $45.55$ |
| SDSS J093532.45+534836.5 | $<1.0$ | $-25.3$ | $<0.6$ | $0.6864$ | $270$ | $1620 \times 2$ | $760$ | $0.70$ | $43.20$ | $3.73 \pm 0.03$ | $45.26$ |
| SDSS J114147.78+104345.9 | $<1.0$ | $-25.3$ | $<0.5$ | $0.6785$ | $0$ | $1620 \times 2$ | $760$ | $0.54$ | $43.30$ | $4.68 \pm 0.20$ | $45.24$ |
| SDSS J212452.10+211505.1 | $<2.5$ | $-25.1$ | $<0.6$ | $0.4752$ | $284$ | $1620 \times 2$ | $800$ | $0.45$ | $42.78$ | $3.58 \pm 0.10$ | $45.08$ |

Notes. (1) Object name. (2) Observed radio flux at 1.4 GHz in mJy, taken from the FIRST survey (Becker, White & Helfand 1995; White et al. 1997) and the NVSS survey (Condon et al. 1998, for SDSS J0412–0511 and SDSS J2214+2115). None of the sources with FIRST coverage are detected, so we report here the upper limits for point sources (5σ > 0.25 mJy, Collinge et al. 2005). SDSS J2214+2115 does not have coverage in FIRST and is not included in the NVSS point-source catalogue; thus, we place an upper limit of $f_{1.4\,GHz} \lesssim 2.5$ mJy. (3) Absolute magnitude of the rest-frame B band, derived by convolving the SDSS spectrum to the transmission curve of the Johnson B filter and converting the flux density averaged over the bandwidth ($\Delta \lambda = 940 \, \AA$) to the AB magnitude at the effective wavelength midpoint $\lambda_{eff} = 4450 \, \AA$ (Binney & Merrifield 1998). (4) Radio-to-optical flux ratio, defined as $R = \log (F_{1.4\,GHz}/F_B)$, where $F_{1.4\,GHz}$ and $F_B$ are the rest-frame 1.4 GHz and B-band fluxes, respectively. K-correction for the radio flux is calculated following Zakamska et al. (2004), assuming a power-law spectrum of $F_{\nu} \propto \nu^{-0.5}$. All of our objects satisfy the conventional criterion that requires radio-quiet/weak objects to have $R < 1$ (Kellermann et al. 1989). (5) Redshift, from Shen et al. (2011). (6) Position angle of the shorter axis of the field of view, in degrees east of north. (7) Exposure time in seconds and number of exposures. (8) Central wavelength of the grating R400 used for the object in nm. (9) Full width at half-maximum (FWHM) of the seeing at the observing site, in arcseconds. (10) Total luminosity of the [O III] λ5007 Å line (logarithmic scale, in erg s$^{-1}$), derived from our data calibrated against SDSS spectra. The SDSS DR10 spectra of the sample objects are accurate within $\pm 5$ per cent. We estimate that subtracting continuum and Fe ii contributions is about 20 per cent and that the procedure of flux calibration against SDSS spectra introduces another 10–20 per cent. Thus, the uncertainty of log $L_{[\text{OIII}]}$ is about 15 per cent. (11) Absolute value of the best-fitting power-law exponent of the outer part of the [O III] profile along the major axes (i.e. $I_{[\text{OIII}]} \propto R^{-\alpha}$, see Fig. 5). (12) Luminosity at rest-frame 8 $\mu$m (logarithmic scale, in erg s$^{-1}$), interpolated from WISE photometry.

view, translating to a physical scale of $30 \times 24$ kpc$^2$ at $z = 0.5$, the typical redshift of our sources. The science field of view is sampled by 1000 contiguous 0.2 arcsec diameter hexagonal lenslets, and simultaneous sky observations are obtained by 500 lenslets located $\sim 1$ arcmin away. The seeing at the time of our observations was between 0.4 and 0.7 arcsec (2.4–4.2 kpc at a typical seeing of $\sim 2$ arcsec). The basic information for our quasar sample and the Gemini package for IRAD$^1$, following the standard procedure for G<br>

$^1$ The Image Reduction and Analysis Facility (IRAF) is distributed by the National Optical Astronomy Observatories which is operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation.

$^2$ http://www.gemini.edu/sciops/data/IRAF/doc/gmosinfoifu.html

$^3$ http://www.sdss3.org/dr10

bias correction is applied only once on each image, and (b) we set the parameter ‘weights’ of gfreduce to ‘none’ (in contrast to ‘variance’ as suggested by the standard example) to avoid significantly increased noise in some parts of the extracted spectrum. The final product of the data reduced from each exposure is a data cube with 0.1 arcsec spatial pixels (‘spixels’). The two frames are finally combined using the tasks 'combine' by taking the mean spectra in each spaxel.

2.3 Flux calibration and continuum/Fe II subtraction

We flux-calibrate our data using the spectra of our science targets from the SDSS Data Release 10 (Ahn et al. 2014). SDSS spectra are collected by fibres with a 3 arcsec diameter at a typical seeing of $\sim 2$ arcsec, and SDSS spectrophotometric calibrations are likely good to 5 per cent or better (Adelman-McCarthy et al. 2008). Since SDSS fibre fluxes are calibrated using point spread function (PSF) magnitudes, SDSS spectrophotometry is corrected for fibre losses.

In view of the limited wavelength coverage of our IFU data, we choose the rest-frame wavelength range of 4980–5050 Å which is covered with good sensitivity for all objects to perform the flux calibration. To simulate the SDSS fibre observations, we convolve the IFU image at each wavelength with a Gaussian kernel whose full width at half-maximum (FWHM) satisfies FWHM$^2 + \text{seeing}^2 = 2$ arcsec$^2$ to mimic the SDSS observing conditions, and then we extract the spectrum using a 3$''$-diameter circular aperture. We then collapse the spectrum between rest-frame 4980 and 5050 Å and compare the resultant flux to that of the SDSS spectrum after
converting SDSS vacuum wavelengths to air. The calibration of the SDSS data includes a PSF correction to recover the flux outside the fibres assuming a 2 arcsec seeing, which needs to be removed for our purpose. In the last step of our calibration, we downgrade the image of our standard star to 2 arcsec resolution and find that a 3 arcsec circular aperture centred on the star encloses \(\sim 80\) per cent of the total flux. This factor is taken into account for the final calibration of the IFU data against the SDSS spectra.

In order to remove the contamination from Fe\(\text{II}\) emission, we fit the continuum in the vicinity of the [O\(\text{III}\)]–H\(\beta\) region with the sum of a polynomial and the Fe\(\text{II}\) template from Boroson & Green (1992). As part of the fit, we smooth the Fe\(\text{II}\) template using a Gaussian kernel, whose width is a free fitting parameter, to take into account that the velocity dispersion of Fe\(\text{II}\) emission varies from object to object. The polynomial is set to be quadratic for all targets with the exception of SDSS J0924+0642, for which cubic functions are necessary to produce reasonable fits. The Gemini spectra after continuum and Fe\(\text{II}\) subtraction, co-added spatially within a circular annulus between 0.5 and 2 arcsec radii, are shown in Fig. 3.

Fe\(\text{II}\) contamination to our [O\(\text{III}\)] analysis is insignificant or negligible in most (10 out of 12) of our targets, because the sample is pre-selected to have low Fe\(\text{II}\) equivalent width. Considerable Fe\(\text{II}\) contamination is present only in SDSS J0304+0022 and SDSS J0924+0642. Specifically, in Fig. 2, the strong Fe\(\text{II}\) contamination in the [O\(\text{III}\)]–H\(\beta\) wavelength region essentially swamps the [O\(\text{III}\)]\(\lambda4959\) Å emission, whereas after Fe\(\text{II}\) and continuum subtraction this feature is revealed with the same velocity structure as the [O\(\text{III}\)]\(\lambda5007\) Å line (Fig. 3).

### 3 [O\(\text{III}\)] Line Fitting and Surface Brightness Maps

For obscured quasars, we created the [O\(\text{III}\)] maps by directly collapsing the data cube over the [O\(\text{III}\)] wavelength range (Liu et al. 2013a). This was possible because the direct emission from the quasar itself is blocked by circumnuclear obscuration. In our sample of unobscured quasars, the analysis is more complicated because the overall emission is dominated by the directly observable continuum and the broad emission lines that originate near the supermassive black hole, rather than in the much more extended host galaxy. Even after we perform continuum and Fe\(\text{II}\) subtraction from the overall spectrum of each spaxel, [O\(\text{III}\)] maps of type 1 quasars are contaminated by the residual continuum.

![Figure 3: Gemini spectra of our quasar sample after continuum and Fe\(\text{II}\) subtraction, spatially collapsed within a circular annulus between 0.5 and 2 arcsec radii. Flux densities are normalized by the peak flux density in the [O\(\text{III}\)]–H\(\beta\) wavelength range. In the integrated spectrum of SDSS J0304+0022 the [O\(\text{III}\)]\(\lambda4959\) Å is not detected, but it is recovered after continuum and Fe\(\text{II}\) subtraction.](image)
Fig. 4. Intensity maps of the \([\text{O} \text{ iii}]\) line in the 12 unobscured quasars in our sample, shown on a logarithmic scale. The tick marks of the colour bars are in units of \(10^{-14} \text{ erg} \cdot \text{s}^{-1} \cdot \text{cm}^{-2} \cdot \text{arcsec}^{-2}\). In each spaxel, the \([\text{O} \text{ iii}]\) flux is calculated from a multi-Gaussian fit to the spectral profile of the line. The seeing at the observing site is depicted by the open circle whose diameter is the FWHM of the PSF. SDSS J0924+0642 is the only object that is likely unresolved.

We can minimize these residuals by taking advantage of the spectroscopic information to better isolate the \([\text{O} \text{ iii}]\) emission through line fitting. In each spaxel, we perform linear continuum + \(N\)-component Gaussian fits to the \([\text{O} \text{ iii}]\) line profiles from the flux-calibrated data cubes following the strategy described in Liu et al. (2013b, section 2.2). As in the case of obscured quasars, we find that a combination of \(N = 1–3\) Gaussians is sufficient for every source in our sample so that the reduced \(\chi^2\) is \(<2\) except for sporadic problematic spaxels. The intensity of the \([\text{O} \text{ iii}]\) line in each spaxel is then computed from the multi-Gaussian fit, not from the observed profile. The final \([\text{O} \text{ iii}]\) surface brightness maps are shown in Fig. 4.

The surface brightness sensitivity (rms noise) of these maps is in the range \(\sigma = (0.5–1.5) \times 10^{-17} \text{ erg} \cdot \text{s}^{-1} \cdot \text{cm}^{-2} \cdot \text{arcsec}^{-2}\).

In Fig. 5, we show a comparison of the surface brightness profiles of the \([\text{O} \text{ iii}]\) emission and quasar continuum with the PSFs. All profiles are extracted using simple circular annuli. To determine the PSF for each observation, we directly measure the FWHM of the seeing from a sample of field stars in the acquisition images taken right before the science exposure. We then use the radial profile of the standard star observed with the IFU, but rescale it in the spatial direction to reproduce the correct FWHM of the science observation.

By comparing the radial profiles of the PSFs and the \([\text{O} \text{ iii}]\) emission, we find that the majority (8/12) of the target \([\text{O} \text{ iii}]\) nebulæ are clearly more extended than the PSF. Among the remaining targets with \([\text{O} \text{ iii}]\) profiles approximating the PSF, 3 quasars (SDSS J0311–0707, SDSS J0753+3153 and SDSS J2124+2115) are marginally resolved, because of unambiguous changes in radial velocity (>160 km s\(^{-1}\)) across their extents (Fig. 6) or variations in their velocity dispersions (Fig. 7). Kinematic differences across
the nebulae give a strong indication that these sources are extended. The remaining object SDSS J0924+0642 is not resolved. Its spatial profile is consistent with the PSF, and its velocity field, although well organized, has a measured maximum velocity difference of only \( \sim 80 \) km s\(^{-1}\), and its velocity dispersion is almost constant in all parts of the nebula.

In order to characterize the physical extents of the nebulae around obscured quasars, we previously defined four different size measures and discussed their advantages and disadvantages (Liu et al. 2013a): \( R_{5\sigma} \), the semimajor axis of the best-fitting ellipse enclosing \( S/N \geq 5 \) spaxels; \( R_{\text{eff}} \), the half-light radius; \( R_{\text{int}} \), the isophotal radius at a surface brightness of \( 10^{-15} \) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\); \( R_{\text{int}} \), the isophotal radius at a surface brightness of \( 10^{-15}/(1+z)^4 \) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\) corrected for cosmological dimming. In Table 2, we report all of these quantities for the [O \text{ III}] line and the first two size measures for the continuum as well. As we pointed out in Liu et al. (2013a), the most physically motivated measure for the [O \text{ III}] extent is \( R_{\text{int}} \), which is independent of redshift and the depth of the data and is thus most suitable for comparing sizes of nebulae from different observations. For the four quasars that are marginally or unresolved, we report the measured sizes as upper limits.

We also create continuum images of our quasars by collapsing the spectrum over a wavelength interval free of line signatures. Depending on the quasar redshift and wavelength coverage of the IFU data, the median wavelength range we use is 4700–5200 Å excluding line emission features. The spatial profiles of the continuum emission are depicted by dashed lines in Fig. 5. The continuum is more compact than the [O \text{ III}] emission, as is expected since it is dominated by the point-like quasar. The continuum emission is approximately consistent with the PSF in about five objects (noted in Table 1), but is resolved or marginally resolved.
in the other objects. The resolved blue continuum may be due to quasar light scattered off of the interstellar matter of the host galaxy (Borguet et al. 2008) or due to star formation in the quasar host (Letawe et al. 2007; Silverman et al. 2009).

4 IONIZED GAS NEBULAE IN UNOBSCURED AND OBSCURED QUASARS

Our observations of the type 1 quasars are well matched to those of the type 2 quasar sample we conducted previously in redshift, [O III] luminosity, and parameters of observations and data reduction. The major difference between the two samples is that the issues related to the PSF of the unobscured quasar need to be addressed carefully for type 1 objects. Because most [O III] nebulae around type 1 quasars are well resolved, we are in a good position to directly compare the ionized gas distribution around the two populations.

4.1 Physical extents and morphology

Unobscured quasars, like their obscured peers, are surrounded by ionized gas nebulae that extend over a spatial scale comparable to the typical size of a galaxy in every case.

Sizes. Taking data from Table 2, we first compare the sizes of the [O III] nebulae using the semimajor axes of the elliptical isophotes fitted at the 5σ surface brightness limit. In the type 2 sample, SDSS J0841+2042 and SDSS J1039+4512 can be categorized as marginally resolved by our standard. Excluding marginally or unresolved targets from both samples, we find the median and the standard deviation of the detected [O III] nebulae to be \( \langle R_{5\sigma}^{T1} \rangle = 13.3 \pm 2.0 \) for the unobscured sample and \( \langle R_{5\sigma}^{T2} \rangle = 14.1 \pm 3.6 \) for the obscured quasars, and \( \langle R_{5\sigma}^{int} \rangle = 10.7 \pm 1.7 \) for the unobscured objects and \( \langle R_{5\sigma}^{int} \rangle = 12.9 \pm 3.4 \) for the obscured ones when \( R_{5\sigma} \) (sizes of the nebulae at a cosmologically corrected fixed surface brightness limit) is considered. To compare the survival distributions of the two samples with censored data, we perform the logrank test.

Figure 6. The line-of-sight velocity maps of our quasars, in km s\(^{-1}\). In every spaxel, we use multi-Gaussian fits to the [O III] emission line to determine the median line-of-sight velocity. These values are determined relative to the overall quasar redshift (as measured by the SDSS pipeline by fitting a quasar template to the overall fibre spectrum) and may be different by a few tens of km s\(^{-1}\) from the redshift of the host galaxy (Liu et al. 2013b). Only spaxels where the peak of the [O III] λ5007 Å line is detected with S/N > 5 are plotted.
Similarity of type 1 & type 2 quasar nebulae

Figure 7. The maps of the $W_{80}$ parameter (measured in km s$^{-1}$) for the type 1 quasars in our sample. $W_{80}$ is a measure of the line-of-sight velocity dispersion of the emission-line gas. For a Gaussian profile, $W_{80} = 1.088 \times \text{FWHM}$, and for the heavy-winged line profiles characteristic of our objects, $W_{80} > 1.088 \times \text{FWHM}$. Only spaxels where the peak of the [O III] $\lambda 5007$ Å line is detected with S/N > 5 are plotted.

using the `twosampt` task from the IRAF STSDAS package, finding the probabilities that they are drawn from the same parent distribution are 0.57 and 0.39 for $R_{50}$ and $R_{int}$, respectively. We therefore conclude that no significant difference is seen between the two samples in their sizes, though the nebula of the unobscured quasars appear slightly more compact than those of the obscured sample, and the fraction of marginally or unresolved objects is slightly higher (type 1: 4/12, type 2: 2/11).

Morphology. In addition to the similar spatial extents, the unobscured quasar nebulae show regular morphology and are nearly perfectly round, which is also very similar to the obscured sample. With marginally or unresolved objects excluded from both type 1 and type 2 samples, the median ellipticity measured at a surface brightness of $10^{-15}/(1 + z)^4$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ is $\langle \epsilon_{int}^T \rangle = 0.14 \pm 0.11$ for the unobscured objects and $\langle \epsilon_{int}^T \rangle = 0.14 \pm 0.11$. The logrank test gives a probability of 1.00 that both samples follow the same distribution. Therefore, we do not observe significant morphological difference between the two samples.

Radial profiles. The radial distribution of [O III] emission from the unobscured quasars also follow loci very similar to those of the obscured sample. When the outer ($R \gtrsim 1$ arcsec) part of the [O III] surface brightness profile is fit by a power law $I_R \propto R^{-\eta}$ and the four marginally or unresolved quasars are excluded, we find that the best-fitting exponent $\eta$ ranges from 2.58 to 4.68 (Table 1) and has a median $\langle \eta^T \rangle = 3.88 \pm 0.70$, well consistent with the results from the obscured quasar sample which has $\eta = 3.00$–5.70 and a median value of $\langle \eta^T \rangle = 3.53 \pm 0.87$. The logrank test shows that the probabilities that the two samples are drawn from the same parent distribution is 0.28.

Hence, we conclude that no significant difference in sizes, morphology or radial distribution is seen between the gas nebulae of unobscured and obscured quasar samples.
G. Liu, N. L. Zakamska and J. E. Greene

after excluding the $R/\Delta v_1$ values to minimize the $\epsilon_1$ between 2 $/ \Delta 1 v$ $\epsilon_1$ $K-W$III $6 \times v$ $-$ III $\lambda b(Liu et al.) \sim 2 W$ and $-\nu$ values in their respective III $\geq -5$ in the $[O \nu] / \Delta 1 v$ $\lambda$ line emission (semimajor axis in kpc). (8, 9) Isophotal radius (semimajor axis, in kpc) and ellipticity at the observed limiting surface brightness of $10^{-16}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. (10, 11) Isophotal radius (semimajor axis, in kpc) and ellipticity at the intrinsic limiting surface brightness (corrected for cosmological dimming) of $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. (12) Maximum median velocity range across the kinematic maps of the nebulae (see Fig. 6), in km s$^{-1}$. For each object, the 5 per cent tails on either side of the distribution of median velocities are excluded for determination of $\Delta v_{\text{max}}$ to minimize the effect of the noise. (13, 16, 17) Widths $W_0$ (km s$^{-1}$), asymmetries $A$ and kurtosis $K$ values of the integrated $[O \nu] \lambda 5007$ Â line profiles, measured from the SDSS fibre spectrum. (14) Maximum $W_0$ and most negative $v_{\text{OII}}$ values in their respective spatially resolved maps (km s$^{-1}$). Like for $\Delta v_{\text{max}}$, the 5 per cent tails on either side of their respective distributions are excluded. (15) Observed percentage change of $W_0$ per unit distance from the brightness centre, in units of per cent kpc$^{-1}$. It is defined as $\Delta W_0 \equiv \Delta W_0/R_0$, where $R_0$ is the maximum radius for the region where the peak of the $[O \nu] \lambda 5007$ Â line is detected with $S/N \geq 5$, and $\Delta W_0 = 100 \times (W_{0, \text{max}} - W_{0, \text{R}=0})/W_{0, \text{R}=0}$.

### 4.2 Kinematic properties

To characterize the line-of-sight velocity and velocity dispersion of the ionized gas, in every spaxel we use the multi-Gaussian fits to the $[O \nu]$ line to measure the median velocity ($v_{\text{med}}$) and the velocity interval that contains 80 per cent of the total emission centred at the median velocity ($W_0$). These parameters, first introduced by Whittle (1985), were also used to characterize the kinematics of the $[O \nu]$ emission in the obscured quasar sample (Liu et al. 2013b). The spatial distributions of $v_{\text{med}}$ and $W_0$ are shown in Figs 6 and 7. Across every nebula, the median velocity of $[O \nu]$ emission varies by up to a few hundred km s$^{-1}$. Although some noisy spaxels are present, most of the velocity variation proceeds in a smooth fashion from one spaxel to the next, which implies that the velocity profiles of $[O \nu]$ vary among the spaxels. The well-resolved velocity structure confirms that the $[O \nu]$ emission is spatially resolved in our targets. Several of the objects show well-organized velocity structures, with blueshifted emission predominantly on one side of the nebula and redshifted emission predominantly on the other and with the line of nodes centred at the brightness peak (e.g. SDSS J0304+0022, SDSS J0311−0707 and SDSS J0935+5348).

In Table 2, we report the maximum difference in $v_{\text{med}}$ between the redshifted and the blueshifted regions $\Delta v_{\text{max}}$ after excluding the 5 per cent highest and 5 per cent lowest $v_{\text{med}}$ values to minimize the effect of noise. The maximum projected velocity difference ranges between 83 and 576 km s$^{-1}$ among the 12 obscured quasars. The same measurement performed in the obscured sample yielded values of 89–522 km s$^{-1}$ (Liu et al. 2013b).

The $[O \nu]$ velocity widths are just as high as those seen in type 2 quasars. Both the luminosity-weighted overall ($W_0$) (measured from the SDSS fibre spectra which capture the integrated emission from the nebulae) and the maxima of $W_0$ in the spatially resolved maps (excluding the 5 per cent highest values) are listed in Table 2. The maximal values are $\sim 1000$ km s$^{-1}$ or greater in most of the sample, reaching 2000 km s$^{-1}$. The object with the smallest line-of-sight velocity dispersion appears to be SDSS J0753+3153 which has a nearly constant $W_0 \sim 300$ km s$^{-1}$ across the nebula.

In Fig. 8, we show the distributions of the overall line widths ($W_0$) and the maximum velocity difference $\Delta v_{\text{max}}$ for both type 1 and type 2 quasars. Excluding the only likely unresolved target, SDSS J0924+0642, we do not find a significant difference between ($W_0$) values in type 1 and type 2 objects, with the Kolmogorov–Smirnov (K–S) test giving a $p = 0.37$ probability that they are drawn from the same distribution. The median $\Delta v_{\text{max}}$ is slightly larger in the unobscured sample ($\langle \Delta v_{\text{max}}^{\text{1}} \rangle = 238 \pm 138$ km s$^{-1}$) than in the obscured quasars ($\langle \Delta v_{\text{max}}^{\text{2}} \rangle = 161 \pm 146$ km s$^{-1}$), although the
difference is not statistically significant (the K–S test yields probability $p = 0.15$ that the two samples follow the same distribution).

We find no correlation between the two quantities for the obscured sample (Liu et al. 2013b). A weak correlation might exist among the unobscured quasars (the Kendall rank correlation coefficient $\tau = 0.60$ with probability $p = 0.01$ that no correlation is present).

The radial profiles of $W_{\alpha}$ are almost flat at projected distances $R \lesssim 5$ kpc. At larger radii, the scatter increases with $R$, while $W_{\alpha}$ appears to decrease in 10/12 of the sample (by $\sim 5$ per cent per kiloparsec from the brightness centre) and remains roughly constant in the two remaining objects (J0753+3153 and J0924+0642). This is very similar to the profiles seen in type 2 quasars. As we discussed previously (Liu et al. 2013b), at least some of this decline is due to the decrease in the signal-to-noise ratio which prevents us from fitting multiple Gaussian components to the [O III] emission. However, we concluded that this effect was not sufficient to explain the entirety of the $W_{\alpha}$ decline and that it was likely that the line-of-sight velocity width was in fact slightly decreasing with projected distance. Given the similarity of $W_{\alpha}$ profiles between the two samples, the same arguments apply for the unobscured quasars as well. A declining $W_{\alpha}$ radial profile becomes more plausible when the PSF smearing effect is taken into account, which makes the high $W_{\alpha}$ values in the centre spill into outer regions and thus flattens the overall radial profile.

We measure line asymmetry $A$ for the integrated [O III] emission (tabulated in Table 2) as well as for every spaxel. Asymmetry is defined as $A = ((v_{\text{red}} - v_{\text{ned}}) - (v_{\text{ned}} - v_{\text{blue}}))/W_{\alpha}$, based on velocities at 10 and 90 per cent of the cumulative line flux. For lines with blueshifted excess, this value is negative; this is what is predominantly seen in our sample. Negative line asymmetries strongly suggest that at least some of the narrow-line-emitting clouds form an outflow whose redshifted part (directed away from the observer) is partly extincted by the dust in the quasar host galaxy (Heckman et al. 1981; Whittle 1985). The distribution of asymmetries in unobscured quasars is statistically indistinguishable from that in obscured ones (the K–S test gives a probability $p = 0.62$ that they are drawn from the same distribution). Similarly, the measurements of the shape parameter $K = W_{\alpha}/(1.397 \times \text{FWHM})$ (defined via the velocity width enclosing 90 per cent of the flux) indicate that [O III] profiles in type 1 quasars have heavier wings than a Gaussian and that the typical shapes of the [O III] lines in type 1 and type 2 quasars are similar ($p = 0.20$ as given by the K–S test).

5 DISCUSSION

5.1 Size–luminosity relation

It would seem reasonable that quasars with higher luminosity would have larger photoionized nebulae around them. The number of photons available for photoionization varies with distance from the quasar $r$ as $\propto L_{\text{bol}}/4\pi r^2$. Therefore, in the simplest possible model – in which the density of particles within the line-emitting clouds is the same everywhere – the size of a region with a given ionization parameter is $\propto L_{\text{bol}}^{1/2}$. If the narrow-line luminosity is an accurate indicator of the bolometric luminosity with $L_{\text{bol}} \propto \alpha L_{\text{bol}}$, then the [O III] sizes and luminosities of nebulae should be related via $R \propto L_{\text{bol}}^{0.5}$. Somewhat shallower slopes (down to 0.33) can be obtained under other assumptions about the $L_{\text{bol}}$–size relation (Schmitt et al. 2003; Bennett et al. 2006; Hainline et al. 2013).

The observed slope of the size–luminosity relation is significantly shallower than these simple estimates. By combining measurements of [O III] sizes in quasars with those in Seyfert 2 galaxies, Greene et al. (2011) found a slope of $0.22 \pm 0.04$. Liu et al. (2013a) supplemented these observations with 11 objects at the very luminous end and used the same uniform distance-independent definition of nebular size $R_{\text{int}}$ to find an exponent of $0.25 \pm 0.02$. Incorporating our data points and observations from Hainline et al. (2013) and Husemann et al. (2013) does not lead to significant changes to the slope. In fact, taking into account the marginally or unresolved sources as upper limits of $R_{\text{int}}$, we perform the Bayesian linear fit employed by Liu et al. (2013a), which uses Markov Chain Monte Carlo to calculate the posterior probabilities (Kelly 2007), and find the following best-fitting relation (Fig. 9):

$$\log \left( \frac{R_{\text{int}}}{\text{pc}} \right) = (0.23 \pm 0.02) \log \left( \frac{L_{\text{bol}}^{\text{[O III]}}}{10^{42} \text{erg s}^{-1}} \right) + (3.72 \pm 0.02).$$

The observed shallow slope of the size–luminosity relationship likely indicates that the clouds located in the outer part of the gas nebulae around luminous quasars are matter bounded (as implied by the line ratio measurements), i.e. the gas is fully ionized, and the recombinant rate cannot keep up with the ionization rate (Liu et al. 2013a).

Because the conversion from $L_{\text{bol}}$ to $L_{\text{bol}}^{\text{[O III]}}$ involves a somewhat uncertain slope, Hainline et al. (2013) suggest using a more direct measure of the bolometric luminosity, for example the luminosity at rest-frame 8 $\mu$m which traces emission from the warm to hot dust near the supermassive black hole and thus should be a good measure of the power of the central engine. We obtain the rest-frame $vL_{\nu, 8 \mu\text{m}}$ by spline interpolating the photometry from the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) which provides all-sky catalogues at 3.4, 4.6, 12 and 22 $\mu$m.

Based on two objects from Husemann et al. (2013) and Liu et al. (2013a), Hainline et al. (2013) report a tentative flattening of the relationship at the high-luminosity end, suggesting the existence of an upper limit on the size of the narrow-line region beyond which the increase in quasar luminosity does not result in an increase in the size of the narrow-line region. As seen from Fig. 9, the addition of our sample strengthens this finding: our data yield six quasars (half of the sample) that have $vL_{\nu, 8 \mu\text{m}} > 10^{45.5}$ erg s$^{-1}$ but $R_{\text{int}} \lesssim 11$ kpc, so that the total number of quasars in this regime reaches eight. Excluding these objects, we perform the Bayesian linear fit employing Markov Chain Monte Carlo used by Liu et al. (2013a) again and find a best-fitting linear relation for the targets with $vL_{\nu, 8 \mu\text{m}} < 10^{45.5}$ erg s$^{-1}$:

$$\log \left( \frac{R_{\text{int}}}{\text{pc}} \right) = (0.37 \pm 0.03) \log \left( \frac{vL_{\nu, 8 \mu\text{m}}}{10^{42} \text{erg s}^{-1}} \right) + (3.63 \pm 0.03).$$

This result is consistent with that of Hainline et al. (2013, slope $\approx 0.41 \pm 0.02$, intercept $\approx 3.65 \pm 0.02$) and is depicted by a dotted line in Fig. 9. If the flattening is characterized by a plateau, we find the following best-fitting piecewise linear fit for all data points but the upper limits:

$$\log \left( \frac{R_{\text{int}}}{\text{pc}} \right) = \begin{cases} 
(0.44 \pm 0.02) \log \left( \frac{vL_{\nu, 8 \mu\text{m}}}{10^{44} \text{erg s}^{-1}} \right) + (3.64 \pm 0.02) & \text{for } vL_{\nu, 8 \mu\text{m}} < 10^{44.95\pm0.06} \text{ erg s}^{-1}; \\
4.06 \pm 0.01 & \text{for } vL_{\nu, 8 \mu\text{m}} \geq 10^{44.95\pm0.06} \text{ erg s}^{-1}.
\end{cases}$$
Figure 9. Size–luminosity relation of the radio-quiet/weak unobscured quasars from our sample (filled circles) in terms of \([\text{O III}]\) (top) and mid-IR (bottom) luminosities. Also included are previous observations of type 2 quasars (Humphrey et al. 2010; Greene et al. 2011; Hainline et al. 2013; Liu et al. 2013a), type 1 quasars (Husemann et al. 2013) and Seyfert 2 galaxies (Fraquelli, Storchi-Bergmann & Levenson 2003; Bennert et al. 2006). \(R_{\text{int}}\) is the isophotal radius at the surface brightness of \(10^{-15}/(1+z)^4\) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\) (Liu et al. 2013a) and \(\nu L_{\nu,8\mu m}\) is the rest-frame 8 \(\mu\)m luminosity obtained by interpolating between \textit{WISE} bands. Our linear fit to the \(R_{\text{int}}\) versus \([\text{O III}]\) relation results in a slope of 0.23 \(\pm\) 0.02 (solid black line), consistent with Liu et al. (2013a, 0.25 \(\pm\) 0.02, grey line). Our best-fitting piecewise linear fit to the \(R_{\text{int}}\) versus \(\nu L_{\nu,8\mu m}\) relation (solid black line) has a slope of 0.44 \(\pm\) 0.02, a break at \(\log \nu L_{\nu,8\mu m} = 44.95 \pm 0.06\), a maximum radius of \(\log R_{\text{max}}/(\text{pc}) = 4.06 \pm 0.01\), well consistent with the result of Hainline et al. (2013, grey line). For the objects with \(\nu L_{\nu,8\mu m} < 10^{45.5}\) erg s\(^{-1}\), we find a best-fitting slope of 0.37 \(\pm\) 0.03.
This piecewise linear equation is shown by a solid black line in the same figure, and is also in good agreement with Hainline et al. (2013), slope = 0.47 ± 0.02, intercept = 3.67 ± 0.02, break luminosity = $10^{40.86 ± 0.03}$ erg s$^{-1}$ and the limiting radius = $10^{4.07 ± 0.03}$ pc.

We must be cautious in interpreting the flattening seen in Fig. 9. In particular, our type 1 quasars have been intentionally selected to be matched in [O iii] luminosity to the type 2 quasars from Liu et al. (2013a,b), and yet the former appear to be more luminous by a factor of $\sim 3$ than the latter in mid-infrared (mid-IR). The significant IR-to-[O iii] ratio difference points to the intrinsic difference in the spectral energy distribution (SED) of the two populations. The mid-IR continuum of type 2 quasars is much redder than that of type 1s (Liu et al. 2013b), which likely means that even the mid-IR emission is not an entirely isotropic luminosity indicator. Specifically, the slopes of the IR SEDs (defined as $\nu L_\nu \propto \nu^\alpha$) measured between rest-frame 5 and 12 $\mu$m are $\alpha = -0.33 ± 0.27$ for the type 1 sample (median and standard deviation) and $\alpha = -1.13 ± 0.55$ for the type 2 sample. In type 2 objects, the thermal emission from hot dust seen at mid-IR wavelengths can be affected by obscuration when propagating through the surrounding much colder material in order to reach the observer, which would result in both its reddening and overall suppression. This hypothesis is further strengthened by the observation that many type 2 quasars show silicate absorption which is a byproduct of this process (Knacke & Thomson 1973; Hao et al. 2005; Zakamska et al. 2008). If the [O iii] line is a more or less isotropic indicator of the bolometric luminosity of the quasar, then type 1s would appear more luminous in the mid-IR than their [O iii]-matched type 2 counterparts, as we see in Fig. 9. Ryan C. Hickox et al. (private communication) find a similar ($0.3$–0.4 dex) difference at $L_{[O \text{ iii}]} > 10^{43}$ erg s$^{-1}$ between the type 1 and 2 SEDs when averaged over large SDSS samples. Our knowledge of the details of the mid-IR opacity curve of dust suffers from large systematic uncertainties (Smith et al. 2007). To crudely estimate the amount of extinction necessary to produce such difference in colour between type 1 and type 2 quasars, we assume that dust opacity is $\propto 1/\lambda$ over optical-to-IR range and compute reddening in the simplistic 'screen of cold dust' approximation. To produce a $>0.3$ dex reddening of the unobscured quasar continuum in the 5–12 $\mu$m range, $A_V > 13$ mag worth of dust obscuration would be required, in line with typical limits on the amount of obscuration in type 2 objects (Zakamska et al. 2004; see also Cleaney et al. 2007; Haas et al. 2008; Lacy et al. 2013 for extinction studies in mid-IR).

Thus, there are two possible interpretations of Fig. 9. The first is that the 8 $\mu$m monochromatic luminosity is an accurate probe of the bolometric luminosity of quasars regardless of the type; then, we must conclude that our new sample of unobscured quasars is 0.3 dex more intrinsically luminous than the sample of the obscured ones. In this case, since $R_{[O \text{ iii}]}$ and $L_{[O \text{ iii}]}$ are so similar between the two, this implies that there exists an upper limit on both the size (10 kpc) and the luminosity of the narrow-line region and neither of these values further increases with bolometric luminosity.

The second interpretation is that $L_{[O \text{ iii}]}$ is a reasonably isotropic measure of quasar luminosity, unbiased with respect to quasar type. Then the difference in the 8 $\mu$m luminosity is due to circumnuclear obscuration. As for the sizes, $R_{[O \text{ iii}]}$ are statistically indistinguishable in type 1 and type 2 samples, and we are unable to comment on the existence of the upper limit to the size, since our new data do not in fact lead to an increase in the range of intrinsic luminosities probed. We are inclined to accept this latter interpretation because the mid-IR SEDs of the two samples are undeniably different. In order to reliably probe the flattening of the size–luminosity relationship (Netzer et al. 2004), objects with higher [O iii] and IR luminosities must be observed and quasars of different types need to be considered separately.

The derived $B$-band absolute magnitude of our sample is $-25.6 ± 0.7$ mag on average (Table 1), higher than that of the 19 radio-quiet type 1 quasars studied in Husemann et al. (2008) and Husemann et al. (2013) located at $z = 0.06–0.24$ ($-23.5 ± 0.08$ mag). The detection rate of extended nebulae around our radio-quiet/weak quasars (11/12) is significantly higher than that of theirs (6/19), but the physical extents are comparable (Fig. 9). Among their six detected radio-quiet nebulae, three show one-sided or biconical morphology and the rest are round, in contrast to our quasar nebulae that are morphologically smoother and rounder in every case (ellipticity $\sim 0.1$).

5.2 [O iii]-to-Hβ ratio

The [O iii]-to-Hβ ratio is a powerful diagnostic of ionization conditions in the nebula. In particular, in type 2 quasars this ratio remains nearly constant over most of the nebula and then rapidly declines with the distance from the central source, which we interpret as the signature that the line-emitting clouds become fully ionized and matter-bounded in the outer parts of the nebulae (Liu et al. 2013a). In type 1 quasars, this is a difficult measurement to replicate because of the contribution to the Hβ profile from the broad-line region of the quasar.

To perform this measurement, in every spaxel we subtract the overall quasar continuum and Fe ii, and then we fit the Hβ line using a combination of Gaussians to isolate the narrow component. In eight cases, only two Gaussian components are sufficient – one for the broad component and one to the narrow one. The resulting radial profiles of the [O iii]/Hβ ratio are similar to the ones we found in type 2 quasars, that is, the ratio persists at a constant value ($\sim 10$) within a radius of $R_{\text{crit}} \approx 5–9$ kpc (7 kpc on average) from the centre, and beyond this distance we detect a marginal decline in [O iii]/Hβ([narrow]. In the remaining four objects, the spectral decomposition of Hβ into a narrow and a broad component is highly uncertain, even using the spatially integrated spectra.

For three objects, we show in Fig. 10 the spectra collapsed within two circular annuli that are within and beyond the break radius, respectively. The narrow Hβ component becomes stronger relative to the broad Hβ component in the outer parts, indicating that the narrow Hβ, like the [O iii], is spatially resolved while the broad emission is not. Furthermore, the ratio [O iii]/Hβ([narrow] is marginally smaller, which is especially visible in the bottom panel for SDSS J2214+2115.

In summary, despite the difficulties associated with the emission from the broad-line region of the quasar, we are able to measure the [O iii]/Hβ([narrow] ratios in the extended nebulae around type 1 quasars. We tentatively detect a decline of this ratio in the outer parts of the nebulae, beyond the break radius, which we interpret as due to the clouds becoming overionized (or matter bounded), by analogy to our findings in type 2 quasars. In that case, our hypothesis was supported by the increase in the He ii 4686 Å-to-Hβ ratio in the outer parts of the nebulae (Liu et al. 2013a), which we cannot determine in type 1 quasars because of the contamination from the broad-line region, but even without this additional diagnostic it appears that the ionization conditions are very similar in type 1 and type 2 samples. Therefore, the uniform size of the nebulae is likely set by the pressure profile (which in turn determines the ionization conditions in the gas) and not necessarily by the presence or absence of gas.
The main result of this paper is the striking similarity of the ionized nebulae around obscured and unobscured radio-quiet/weak quasars at a matched [O iii] luminosity. The physical extents, shapes, morphologies and ionization conditions of the nebulae in the two samples are very similar. Neither sample is dominated by illuminated merger debris which would appear as spatially and kinematically separated clumps with relatively small velocity dispersion (Fu & Stockton 2009). The roundness of nebulae in both samples and the similarity of nebular sizes between type 1 and type 2 samples point to wide-angle illumination patterns, which would make the appearance of the nebulae relatively insensitive to the position of the observer.

We previously demonstrated that the large line widths combined with relatively small velocity differences across the nebulae point to quasi-spherical outflows with typical velocities of \(\sim 800\) \(\text{km s}^{-1}\) (Liu et al. 2013b). Alternative explanations, such as host galaxy rotation, fall short of explaining the combination of morphological and kinematic data. In particular, the velocity widths of the emission lines are too high to be comfortably accommodated by the rotation of a disc galaxy, and the ubiquitous blueshifted asymmetry of the lines in both samples also points to gas in outflow. Furthermore, the nebulae are too large and too round to be produced in inclined galaxy discs, not to mention that luminous type 2 quasars predominantly reside in elliptical hosts (Zakamska et al. 2006) and that the presence of large galactic discs would have likely produced systematic differences in the type 1 and type 2 samples.

Thus, the outflow hypothesis still provides the most natural explanation for our data for both type 1 and type 2 samples. At typical velocities of \(\sim 800\) \(\text{km s}^{-1}\), the lifetimes of the nebulae is set by the gas travel time to 13–14 kpc, roughly \(10^7\) yr, comfortably close to the typical lifetime of luminous quasars (Martini & Weinberg 2001; Martini 2004).

However, given the close similarity of nebulae in type 1 and type 2 sources we run into a potential problem. How can all quasars, both obscured and unobscured, show these large ionized regions with long inferred lifetimes? For instance, in a classic ‘blow-out’ picture (Sanders & Mirabel 1996; Hopkins et al. 2006), we might expect that the type 1 objects have already expelled the majority of their gas, leaving themselves bare. Instead, we see no discernible differences between the obscured and unobscured sources.

One possible solution to this problem is that instead of pushing the gas out of the galaxy, the quasars are simply lighting up pre-existing gas, but then we still have the puzzle of what brought the gas out to 13–14 kpc and moving with velocities that are inconsistent with the dynamical equilibrium of the gas within the host galaxy. Perhaps the gas was brought there by a previous episode of quasar activity (Ciotti & Ostriker 2001) or even by starburst-driven winds (Heckman, Armus & Miley 1990), although the typical velocities of the gas seen in our sample are more consistent with quasar-driven feedback than with starburst-driven feedback (Rupke & Veilleux 2013; Hill & Zakamska 2014). Nevertheless, the halo gas has been found to commonly surround all galaxies, being either early type or star forming (Thom et al. 2012). The discovery of the probably pristine halo gas offers an alternative possibility that our quasars are actually lighting up circumgalactic gas in a non-equilibrium but almost steady state.

Another solution – one that does not involve appealing to a previous episode of activity – is to apply the purely geometric unification model, which is to say that type 1 and type 2 quasars in the two samples are intrinsically very similar and are at the same evolutionary stage. Then, it would be unsurprising to find that the large-scale distribution of ionized gas, relatively unaffected by the circumnuclear obscuration, is similar in the two samples. In fact, for a bimodal model of quasar illumination (as commonly seen in Seyfert galaxies; Mulchaey, Wilson & Tsvetanov 1996a,b) we expect to see somewhat smaller nebular sizes in type 1 objects (which are viewed closer to on-axis) than in type 2 sources according to the standard geometric unification model, and in fact we do see a small (although not a statistically significant) difference in nebular sizes between the two samples, \(R_{\text{int}} = 10.7 \pm 1.7\) kpc for type 1s versus \(12.9 \pm 3.4\) kpc for type 2s. The purely geometric unification model is indirectly supported by \textit{HST} images and spectropolarimetric observations of type 2 quasars (Zakamska et al. 2005, 2006). These observations show that our type 2s are definitely seen as type 1s along some directions, although this does not guarantee that the type 1 and type 2 samples we observed with Gemini IFU are drawn from the same intrinsic distribution of obscuration covering factors. In fact, this difference is also in line with the theoretical evolutionary scenarios that anticipate unobscured quasars to be relatively gas poor, because they are in the post-‘blow-out’ phase when the gas that fuels both quasar activity and star formation has been expelled from the host galaxy.

If we postulate that the type 1 and type 2 samples are intrinsically very similar and the gas seen in the haloes of their host galaxies got there as a direct result of the ongoing quasar activity, then we find that both type 1 and type 2 quasars are we observing are at the same – and fairly advanced – evolutionary stage. It is quite possible that these findings are strongly predicated on the exact method of...
target selection. Indeed, in this paper we study type 1 and type 2 objects of very similar – and very high – [O \text{III}] luminosities. It is likely that such luminosities are not characteristic of earlier or later stages of quasar feedback. In particular, in later stages of feedback one can expect to see diffuse gas at large distances from the quasar which does not necessarily manifest itself in line emission at optical wavelengths, so the [O \text{III}] luminosity expected in such object would be low and it would be missed by our survey. At the other extreme, the initial acceleration and propagation of the outflow – the ‘blow-out’ phase (Sanders & Mirabel 1996; Hopkins et al. 2006) – could be so dust enshrouded that the photoionization of the clouds by the quasar is suppressed, so that again the narrow-line region emission is weak and such object would not be observed in our study. Therefore, in order to identify quasars at varying stages of the quasar feedback process it is important to diversify target selection methods. Perhaps, red quasars (Glikman et al. 2007; Georgakakis et al. 2009) or FeLoBAL quasars (Farrah et al. 2007; Faucher-Giguère & Quataert 2012) represent a young population and are therefore worthwhile targets to examine in the search of the younger phase of quasar-driven winds.

6 CONCLUSIONS

In this paper, we examine the morphology and kinematics of the ionized gas around 12 unobscured (type 1) quasars using data from Gemini GMOS IFU. These objects are well matched in luminosity, redshift and observational setup to the sample of 11 obscured (type 2) quasars we studied previously using the same method (Liu et al. 2013a,b). Observations of ionized gas around type 1 quasars are notoriously difficult because of the emission from the bright central point-like source. Continuum, Fe \text{II} and broad H\text{\beta}, all of which arise close to the supermassive black hole, contaminate the [O \text{III}] and H\text{\beta} emission that arises over the entire host galaxy. We mitigate these difficulties by modelling the spectrum in every spatial element of the field of view and removing the contaminating components.

Extended ionized gas emission is detected in most cases; in a couple of objects, the [O \text{III}] distribution is almost as compact as the PSF, but even in these objects some velocity gradients are seen across the nebula, indicating that faint extended emission is present on top of a bright compact source of [O \text{III}].

The shapes, the morphologies and the surface brightness profiles of the [O \text{III}] emission in type 1 quasars are statistically indistinguishable from those in type 2 objects. The median sizes and the standard deviations are $R_{\text{maj}} = 10.7 \pm 1.7$ kpc for type 1s versus 12.9 $\pm 3.4$ kpc for type 2s, and thus, the nebulae in type 1 objects are slightly smaller than those in type 2s, but given our sample sizes the values are still consistent with being drawn from the same distributions. Similarly, we find no statistical differences between any of the kinematic measures (velocity gradients across the nebulae, line widths, line shape parameters) in the two samples. The [O \text{III}]/H\text{\beta} ratio is much harder to measure in type 1s than in type 2s because of the contamination by the broad-line region of the unobscured quasar, but within the measurement uncertainties this ratio follows the same plateau + decline trend in type 1s as we see in type 2s. The only significant differences between the two samples are in their mid-IR luminosities (higher in type 1s) and mid-IR colours (redder in type 2s) which both suggest that quasar emission is anisotropic even at mid-IR wavelengths, while the [O \text{III}] luminosity is a more isotropic indicator.

The similarity of morphological and kinematic properties between type 1 and type 2 samples suggests that they are intrinsically very similar and that the standard geometry-based unification model of active nuclei (Antonucci 1993) likely applies to these sources. The ionized gas seen around quasars of both types is not in dynamical equilibrium with the quasar host galaxies and is likely in the form of an outflow. If this gas ultimately originated in a compact distribution close to the quasar, then our observations suggest that we are observing both samples at a fairly late evolutionary stage, when most of the gas has already been removed from the galaxy. Our samples of type 1 and type 2 objects were carefully selected to have very similar – and very high – [O \text{III}] luminosities, and therefore, it is perhaps unsurprising that they probe the same evolutionary phase. The search for the earlier (‘blow-out’) and later stages of quasar feedback should continue among other populations which are not necessarily characterized by high narrow-line luminosities.

ACKNOWLEDGEMENTS

NLZ and JEG are supported in part by the Alfred P. Sloan fellowship. GL and NLZ acknowledge support from the Theodore Dunham, Jr. Grant of the Fund for Astrophysical Research. We acknowledge the use of Edward L. Wright’s online cosmology calculator (Wright 2006). This publication makes use of data products from the WISE, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration.

Funding for SDSS-III has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation and the US Department of Energy Office of Science. The SDSS-III website is http://www.sdss3.org/.

SDSS-III is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS-III Collaboration including the University of Arizona, the Brazilian Participation Group, Brookhaven National Laboratory, Carnegie Mellon University, University of Florida, the French Participation Group, the German Participation Group, Harvard University, the Instituto de Astrofísica de Canarias, the Michigan State/Notre Dame/JINR Participation Group, Johns Hopkins University, Lawrence Berkeley National Laboratory, Max Planck Institute for Astrophysics, Max Planck Institute for Extraterrestrial Physics, New Mexico State University, New York University, Ohio State University, Pennsylvania State University, University of Portsmouth, Princeton University, the Spanish Participation Group, University of Tokyo, University of Utah, Vanderbilt University, University of Virginia, University of Washington, and Yale University.

REFERENCES

Adelman-McCarthy J. K. et al., 2008, ApJS, 175, 297
Ahn C. P. et al., 2014, ApJS, 211, 17
Allington-Smith J. et al., 2002, PASP, 114, 892
Antonucci R., 1993, ARA&A, 31, 473
Becker R. H., White R. L., Helfand D. J., 1995, ApJ, 450, 559
Bennert N., Jungwiert B., Komossa S., Haas M., Chini R., 2006, A&A, 456, 953
Binney J., Merrifield M., 1998, Galactic Astronomy. Princeton Univ. Press, Princeton, NJ
Borguet B., Hutsemékers D., Letawe G., Letawe Y., Magain P., 2008, A&A, 478, 321
Boroson T. A., 2002, ApJ, 565, 78
Boroson T. A., Green R. F., 1992, ApJS, 80, 109
Ciotti L., Ostriker J. P., 2001, ApJ, 551, 131
G. Liu, N. L. Zakamska and J. E. Greene

Clowes R., Lawrence C. R., Marshall J. A., Hao L., Meier D., 2007, ApJ, 660, 117
Collinge M. J. et al., 2005, AJ, 129, 2542
Condon J. J., Cotton W. D., Greisen E. W., Yin Q. F., Perley R. A., Taylor G. B., Broderick J. J., 1998, AJ, 115, 1693
Condon J. J., Kellermann K. I., Kimball A. E., Ivezić Ž., Perley R. A., 2013, ApJ, 768, 37
Crotton D. J. et al., 2006, MNRAS, 365, 11
Farrah D., Lacy M., Priddle R., Borys C., Afonso J., 2007, ApJ, 662, L59
Faucher-Giguère C.-A., Quataert E., 2012, MNRAS, 425, 605
Fraquelli H. A., Storchi-Bergmann T., Levenson N. A., 2003, MNRAS, 341, 449
Fu H., Stockton A., 2009, ApJ, 690, 953
Gebhardt K. et al., 1998, AJ, 115, 1693
Glikman E., Helfand D. J., White R. L., Becker R. H., Gregg M. D., Lacy M. et al., 2005, ApJ, 628, L91
González Delgado R., Pérez E., Tadhunter C., Pinezó Delgado R., Pérez E., Tadhunter C., Pérez-Torres M. A., 2010, MNRAS, L113
Haines C. N., Hickox R. C., Greene J. E., Myers A. D., Zakamska N. L., 2013, ApJ, 774, 145
Haines C. N., Hickox R. C., Greene J. E., Myers A. D., Zakamska N. L., Liu G., Liu X., 2014, ApJ, 787, 65
Hao L. et al., 2005, AJ, 129, 1795
Heckman T. M., Armus L., 2009, ApJ, 690, 953
Hill M. J., Zakamska N. L., 2014, MNRAS, 439, 2701
Hopkins P. F., Hernquist L., 2010, MNRAS, 402, 985
Hopkins P. F., Hernquist L., Cox T. J., Di Matteo T., Robertson B., Springel V., 2006, ApJS, 163, 1
Humphrey A., Villar-Martín M., Sánchez S. F., Martínez-Sansigre A., González Delgado R., Pérez E., Tadhunter C., Pérez-Torres M. A., 2010, MNRAS, L113
Husemann B., Wisotzki L., Sánchez S. F., Jahnke K., 2008, A&A, 488, 145
Husemann B., Wisotzki L., Sánchez S. F., Jahnke K., 2013, A&A, 549, A43
Kellermann K. I., Sramek R., Schmidt M., Shaffer D. B., Green R., 1989, AJ, 98, 1195
Kelly B. C., 2007, ApJ, 665, 1489
Knacke R. F., Thomson R. K., 1973, PASP, 85, 341
Lacy M., Sajina A., Petric A. O., Seymour N., Canizal G., Ridgway S. E., Armus L., Storrie-Lombardi L. J., 2007, ApJ, 669, L61
Lacy M. et al., 2013, ApJS, 208, 24
Lehner N. et al., 2013, ApJ, 770, 138
Letaw M., Magain P., Courbin F., Jablonka P., Jahnke K., Meylan G., Wisotzki L., 2007, MNRAS, 378, 83
Liu G., Zakamska N. L., Greene J. E., Nesvadba N. P. H., Liu X., 2013a, MNRAS, 430, 2327
Liu G., Zakamska N. L., Greene J. E., Nesvadba N. P. H., Liu X., 2013b, MNRAS, 436, 2576
Magorrian J. et al., 1998, AJ, 115, 2285
Martini P., 2004, in Ho L. C., ed., Coevolution of Black Holes and Galaxies. Cambridge Univ. Press, Cambridge, p. 169
Martini P., Weinberg D. H., 2001, ApJ, 547, 12
Matsuoka Y., 2012, ApJ, 750, 54
Moe M., Arav N., Bautista M. A., Korista K. T., 2009, ApJ, 706, 525
Mulchaey J. S., Wilson A. S., Tsvetanov Z., 1996a, ApJS, 102, 309
Mulchaey J. S., Wilson A. S., Tsvetanov Z., 1996b, ApJ, 467, 197
Mullaney J. R., Alexander D. M., Fine S., Goulding A. D., Harrison C. M., Hickox R. C., 2013, MNRAS, 433, 622
Murray N., Chiang J., Grossman S. A., Voit G. M., 1995, ApJ, 451, 498
Nesvadba N. P. H., Lehner M. D., De Breuck C., Gilbert A. M., van Breugel W., 2008, A&A, 491, 407
Netzer H., Shenber O., Maiolino R., Oliva E., Croom S., Corbett E., di Fabrizio L., 2004, ApJ, 614, 558
Proga D., Stone J. M., Kallman T. R., 2000, ApJ, 543, 686
Reyes R. et al., 2008, AJ, 136, 2373
Rupke D. N. S., Veilleux S., 2013, ApJ, 768, 75
Sanders D. B., Mirabel I. F., 1996, ARA&A, 34, 749
Schmitt H. R., Donley J. L., Antonucci R. R. J., Hutchings J. B., Kinney A. L., Pringle J. E., 2003, ApJ, 597, 768
Shen Y. et al., 2011, ApJS, 194, 45
Silverman J. D. et al., 2009, ApJ, 696, 396
Smith J. D. et al., 2007, ApJ, 656, 770
Thom C. et al., 2012, ApJ, 758, L41
Thom C. et al., 2012, ApJ, 758, L41
Wagner A. Y., Umemura M., Bicknell G. V., 2013, ApJ, 763, L18
White R. L., Becker R. H., Helfand D. J., Gregg M. D., 1997, ApJ, 475, 479
Whittle M., 1985, MNRAS, 213, 1
Wright E. L., 2006, PASP, 118, 1711
Wright E. L. et al., 2010, AJ, 140, 1868
Zakamska N. L., Greene J. E., 2014, MNRAS, preprint (arXiv:1402.6736)
Zakamska N. L. et al., 2003, AJ, 126, 2125
Zakamska N. L., Strauss M. A., Heckman T. M., Ivezić Ž., Kroll J. H., 2004, AJ, 128, 1002
Zakamska N. L. et al., 2005, AJ, 129, 1212
Zakamska N. L. et al., 2006, AJ, 132, 1496
Zakamska N. L., Gómez L., Strauss M. A., Kroll J. H., 2008, AJ, 136, 1607
Zubovas K., King A., 2012, ApJ, 745, L34

This paper has been typeset from a TeX/LaTeX file prepared by the author.