Ionized outflows in SDSS type 2 quasars at \( z \sim 0.3-0.6 \)∗

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ABSTRACT

We have analyzed the spatially integrated kinematic properties of the ionized gas within the inner \( r \leq \text{few kpc} \) in 13 optically selected SDSS type 2 quasars at \( z \sim 0.3-0.6 \), using the \([\text{OIII}]\lambda\lambda 4959,5007\) lines. The line profiles show a significant asymmetry in 11 objects. There is a clear preference for blue asymmetries, which are found in 9/13 quasars at 10% intensity level. In coherence with studies on other types of active and non active galaxies, we propose that the asymmetries are produced by outflows where differential dust extinction is at work.

This scenario is favoured by other results we find: in addition to quiescent ambient gas, whose kinematic properties are consistent with gravitational motions, we have discovered highly perturbed gas in all objects. This gas emits very broad lines \( (R_{\text{FWHM}}[^{\text{OIII}}] \geq 2) \). While the quiescent gas shows small or null velocity shifts relative to the systemic velocity, the highly perturbed gas tends to show larger shifts which, moreover, are blueshifts in general. Within a given object, the most perturbed gas tends to have the largest blueshift as well. All together support that the perturbed gas, which is responsible for the blue asymmetries of the line profiles, is outflowing. The outflowing gas is located within the quasar ionization cones, in the narrow line region.

The relative contribution of the outflowing gas to the total \([\text{OIII}]\) line flux varies from object to object in the range ~10-70%. An anticorrelation is found such that, the more perturbed the outflowing gas is, the lower its relative contribution is to the total \([\text{OIII}]\) flux. This suggests that outflows with more perturbed kinematics involve a smaller fraction of the total mass of ionized gas.

Although some bias affects the sample, we argue that ionized gas outflows are a common phenomenon in optically selected type 2 quasars at \( 0.3 \lesssim z \lesssim 0.6 \).

Key words: (galaxies:) quasars:emission lines; (galaxies:) galaxies:ISM;

1 INTRODUCTION

Evidence for an intimate connection between supermassive black hole (SMBH) growth and evolution of galaxies is nowadays compelling. Not only have SMBHs been found in many galaxies with a bulge component, but tight correlations exist between the black hole mass and some bulge properties, such as the stellar mass and velocity dispersion \( \sigma \) (Ferrarese & Merritt 2000, Gebhardt et al. 2000). The origin of this relation is still an open question, but quasar induced outflows might play a critical role. Hydrodynamical simulations show that the energy input from quasars can regulate the growth and activity of black holes and their host galaxies (di Matteo, Springel & Hernquist 2005). Such models show that a merger between two galaxies with SMBH leads to strong inflow that feeds gas to the SMBH activating the quasar phase. The energy released by the strong outflows associated with major phases of accretion expels enough gas to quench both star formation and further black hole growth. This determines the lifetime of the quasar phase and explains the relationship between the black hole mass and the stellar velocity dispersion.

This scenario, although very attractive, still lacks compelling observational support. The presence of outflows in different classes of active galaxies has been known for several decades. However, it is still not clear whether they can generate important feedback effects with a notable impact on the systems evolution. The limitations are several, such as...
as the uncertainty on where the outflows originate and their geometry, or the fact that several gas phases (molecular, neutral, ionized) can be involved. These are often observable at different spectral ranges and spatial scales and therefore require different observing techniques.

The presence of outflows of ionized gas in different types of active galaxies is well established. They are evident, for instance, as absorption lines in the UV and X-ray spectra, blueshifted relative to the systemic velocity of the host galaxy. Outflowing velocities of up to ∼2000 km s⁻¹ have been measured (see Crenshaw, Kraemer & George 1992 for a review).

Outflows of ionized gas have also been discovered when characterizing the gas kinematics using the spectral properties of a diversity of forbidden lines in the infrared (e.g. Spoon & Holt 2010) and the optical. The [OIII]λλ4959,5007 lines have been used more frequently in optical studies. These are often the strongest optical lines and have the advantage of being cleanly isolated from other emission and absorption features. In addition, underlying contamination by line emission from the broad line region (BLR) is not expected, as is often the case for permitted lines such as Hα and Hβ.

The predominance of blue asymmetries on the [OIII] line profiles, their frequent blueshift relative to different indicators of the systemic redshift and the kinematic substructure of the lines indicate that the narrow line region (NLR) gas is not a stable, quiescent gas reservoir that follows the bulge gravitational potential. This dynamic behaviour has often been interpreted in terms of outflows where differential reddening is present: i.e. at least part of the NLR gas is moving radially outwards and dust reddening is more severe for the receding gas. This applies to active galaxies in general (e.g. Greene & Ho 2005 and specific AGN types: Seyferts 1 and 2s (Whittle et al. 1988, Colbert et al. 1996, Crenshaw et al. 2010, Heckman et al. 1984), Veilleux 1991), Narrow Line Seyfert 1 galaxies (Bian et al. 2003, Komossa et al. 2008), radio loud and radio quiet type 1 quasars (Leipski & Bennert 2006, Heckman et al. 1984, Boroson 2003) and narrow line radio galaxies at different redshifts (Humphrey et al. 2008, Heckman et al. 1981, Holt, Tadhunter & Morganti 2008, Heckman et al. 1981) found that blue asymmetries are in general not found in steep spectrum (extended) radio sources, but preferentially in radio quiet objects and flat spectrum (compact) radio sources.

The origin of the outflows has also been subject of study. Correlations between the radio properties and the kinematic signatures of the outflows have suggested that the radio jets/lobes can play an important role to trigger such outflows both in radio loud and radio quiet objects (e.g. Humphrey et al. 2008, Leipski & Bennert 2006, Heckman et al. 1984, Whittle et al. 1988, etc.). The dynamics of the ionized gas, which is subject to a partial or full radiation field from the central continuum source, may be affected by the radiation force as well (e.g. Boroson 2005). Finally, galactic superwinds may also exist. Star forming systems at low and high redshift are known to drive galactic winds with observable signatures in the wings of the emission lines (e.g. Shapiro et al. 2003).

Type 2 (obscured) quasars have been discovered in large quantities only in recent years (e.g. Zakamska et al. 2003, Martínez-Sansigre et al. 2003). From the observational point of view, these are the luminous counterparts of Seyfert 2 galaxies. In particular, Zakamska et al. identified in 2003 several hundred objects in the redshift range 0.3 ≤ z ≤ 0.8 in the Sloan Digital Sky Survey (SDSS) with the high ionization narrow emission line spectra characteristic of type 2 AGNs and narrow line luminosities typical of type 1 quasars. Their far-infrared luminosities place them among the most luminous quasars at similar z. Several studies suggest that they have high star-forming luminosities (e.g. Zakamska et al. 2003, Hiner et al. 2009). They show a wide range of X-ray luminosities and obscuring column densities (Ptak et al. 2004, Zakamska et al. 2004). The host galaxies are most frequently ellipticals with irregular morphologies (Zakamska et al. 2004), and the nuclear optical emission is highly polarized in some cases (Zakamska et al. 2003). 15% ± 5% qualify as radio loud (Zakamska et al. 2004, Lal & Ho 2010).

Because of the recent discovery, little is known about the possible existence of outflows in type 2 quasars. Greene et al. (2011) analysed the kinematics of the extended ionized gas in a sample of 15 luminous SDSS type 2 quasars at z < 0.5 in spatial scales of ≤10 kpc. They found kinematically disturbed gas across the host galaxies and proposed that AGN driven outflows are stirring up the gas on scales of kpcs.

We investigate in this paper the presence of ionized gas outflows in a sample of 13 optically selected type 2 quasars at 0.3 ≤ z ≤ 0.6. The observations and data analysis techniques are described in §2. The results are presented in §3 and discussed in §4. The results and conclusions are summarized in §5.

We assume ΩΛ=0.7, ΩM=0.3, H₀=71 km s⁻¹ Mpc⁻¹.

2 OBSERVATIONS AND ANALYSIS

The data were obtained with the Focal Reducer and Low Dispersion Spectrograph (FORS2) for the Very Large Telescope (VLT) installed on UT1 (Appenzeller et al. 1998). The observations were performed in two different runs: 8 and 9th Sept 2008 (4 objects) and 17 and 18 April 2009 (9 objects). All spectra were obtained with the 600RI+19 grism and the GG435+81 order sorting filter. The useful spectral range was ∼5030-8250 Å in the 2008 run and ∼5300-8600 Å in the 2009 run, so that in all cases at least the Hβ and [OIII]λλ4959,5007 lines were within the observed spectral range. The pixel scales are 0.25″ pixel⁻¹ and 0.83 Å pix⁻¹ in the spatial and spectral directions respectively. The spectral resolution, as measured from the sky emission lines, was FWHM=7.2±0.2 Å and 5.4±0.2 Å for the 2008 and 2009 runs respectively. The slit width was 1.3″ in 2008 and 1.0″ in 2009. The observations, data reduction and object sample are described in detail in Villar-Martín et al. (2011, 2010).

1-dim spectra were extracted from spatial apertures centered on the quasars spatial continuum centroid. The sizes were selected to optimize the S/N of the nuclear emission lines, in particular for the detection of faint broad wings. In general, the aperture sizes are ∼1.5″-2″, corresponding to physical sizes ∼7-12 kpc depending on the object. Type 2 quasars are often associated with extended emission line regions (EELR) which can extend sometimes for tens of kpc (e.g. Villar-Martín et al. 2011), well beyond the size of the NLR. The apertures we have defined contain emission from
both the NLR and, when existing, the EELR, although the contribution of the NLR is likely to dominate.

The spectral profiles of [OIII] and Hβ were fitted with the STARLINK DIPSO package. One or more Gaussian components were used depending on the quality of the fits. This was evaluated based both on the errors of the fits and a visual inspection of the residuals. The [OIII] lines are in all cases the strongest and they were used to constrain the expected kinematic substructure of Hβ. The ratio between the [OIII]λ4959,5007 components was forced to be 1:3, in accord with the theoretical value (Osterbrock 1989). Both components were forced to have the same FWHM and in general the separation in wavelength was also fixed. We found necessary to apply these constraints to all kinematic components in order to reject fits that were successful at reproducing the line shapes, but did not have physical meaning.

To start, we attempted to fit the [OIII] profiles with a single Gaussian function, but this failed in all cases and very large residuals remained. The number of Gaussians was progressively increased until a good fit was achieved. Two or three Gaussians at most were required in all quasars. The Hβ line profile could be decomposed in different kinematic components only in some objects where the line had enough signal and was not severely affected by atmospheric or galactic absorption. In those cases, it was assumed that the line consists of the same number of kinematic components as [OIII]. The FWHM and z of each component were constrained from those derived from [OIII]. Only those components with a detectable flux were considered in the final fit of Hβ. Flux upper limits for the non detected components were also estimated. The FWHM (corrected for instrumental broadening in quadrature), the velocity shift relative to the narrow [OIII] core (see §2.1), the flux, the flux relative to the total line flux and the [OIII]/Hβ ratio (when possible) were measured for all kinematics components.

The kinematic measurements obtained for the first 5 objects in Tables 1 and 2 are affected by slit effects (see Villar-Martín et al. 2011). The errors quoted take the resulting uncertainties into account.

The results of the fits are shown in Table 2 and Figures 1 to 13.

### 2.1 The systemic velocity

In order to characterize accurately the gas motions relative to their environment it is essential to determine the systemic redshift $z_{sys}$ of the galaxy. The safest way to do this is to measure the stellar redshift. This is often not possible as for example in studies of type 1 AGNs, high redshift galaxies, etc. where the stellar continuum cannot be isolated from the bright AGN contribution and/or it is not detected with enough signal. In such cases, alternative methods have been applied. Under the assumption that the BLR gas follows gravitational motions, the broad Hβ line centroid has been used to determine $z_{sys}$. For type 2 objects, the [OIII] line fitted with a single Gaussian has often been used instead, both to measure $z_{sys}$ and the stellar velocity dispersion. However, as different works have discussed (e.g. Greene et al. 2011, 2009, Husemann 2011, Boroson 2003, Boroson 2004), this is risky, since the NLR kinematics often reveal non-gravitational motions (see δ1). Indeed, the very asymmetric and sometimes broad [OIII] spectral profiles often make the determination of its own $z$ uncertain by up to 200 km s$^{-1}$ (e.g. Heckman et al. 1981).

There are three objects in our sample with enough signal in the continuum and detected stellar features to try to estimate $z_{sys}$: SDSS J0217-00, SDSS J1337-01 (both with strong stellar features) and SDSS J0123+00 (faint features). For this, we use the full spectral fitting method with the Starlight code (Cid Fernandes et al. 2005), several sets of evolutionary stellar models (González Delgado et al. 2007).
We find that in all three cases there is a variety of models that produce acceptable fits (see one example in Fig. 14). These models allow a range of stellar redshifts which depend mainly on the single stellar population models used as templates for the fits and the weight given to the G band and CaII K stellar absorption features. The allowed redshifts imply a velocity range of \( \sim 100 \text{ km s}^{-1} \), which is the main uncertainty affecting the method.

Although the [OIII] line in the nuclear spectra of our sample is in general quite broad and shows complex kinematic substructure (see $\delta_3$), it shows a very narrow core whose redshift can be estimated with an accuracy of several \( \text{km s}^{-1} \). We will use this as a measurement of $\mathcal{z}_{\text{sys}}$.

In the three objects mentioned above, it is found that this core is at \( \lesssim 100 \text{ km s}^{-1} \) of the stellar velocity, the uncertainty being due to the range of stellar redshifts allowed by the models. Given the difficulty to infer $\mathcal{z}_{\text{sys}}$ from the
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Figure 8. SDSS J1228+00. Line styles and colors as in Fig. 1.

Figure 9. SDSS J1307-02. Line styles and colors as in Fig. 1.

Figure 10. SDSS J1337-01. Line styles and colors as in Fig. 1.

Figure 11. SDSS J1407+02. Line styles and colors as in Fig. 1.

Figure 12. SDSS J1413-01. Line styles and colors as in Fig. 1.

Figure 13. SDSS J1546-00. Line styles and colors as in Fig. 1.
stars in most quasar spectra studied here, we will use the narrow [OIII] core in all objects instead. This method is supported by the results of Greene & Ho (2005). They compared the gaseous and stellar kinematics in the nuclei of a large sample of active galaxies using spectra of somewhat better resolution ($R = \lambda/\Delta \lambda \sim 1800$ vs. $R \sim 900-1400$ at the [OIII] wavelength in our spectra, depending on the object). They found that the FWHM of the [OIII] core, i.e. after the asymmetric wings were removed, and FWHM$_{stars}$ are correlated (although with a large scatter) according to FWHM$_{core}$=(1.24±0.76) × FWHM$_{stars}$.

Based on this result, they propose that FWHM$_{core}$ is a reasonable tracer of the stellar velocity dispersion. It seems reasonable to expect that it also provides a good estimation of the stellar redshift and therefore $z_{sys}$.

Greene et al. (2000) questioned later the validity of this result for luminous obscured AGNs, based on the lack of correlation between the [OIII] FWHM and the stellar velocity dispersion. However, the analysis is based on single Gaussian fits to the emission lines that ignore their complex kinematic substructure. Given the high complexity of the line profiles (see §3.2), it is not surprising that no correlation is found. As Table 1 shows, the FWHM of the core is often noticeably smaller than that resulting from a single Gaussian fit to the line profile.

2.2 The identification of kinematically perturbed gas

We are specially interested in those gas components whose kinematic properties suggest non-gravitational, perturbed motions. In order to identify them, we need to compare the FWHM of each kinematic component with the stellar velocity dispersion FWHM$_{stars}$. Similar values could be explained if the gas is supported by random motions, while rotation would produce narrower FWHM for the gas than for the stars. Broader gas components would imply kinematic perturbation.

In general, it is not possible to measure FWHM$_{stars}$ directly from our spectra. Instead, following Greene & Ho (2005) we will infer the value for each object using FWHM$_{core}$ ($\delta$2.1). Although the scatter of the correlation between these two parameters produces large uncertainties, the FWHM$_{core}$ values in Table 1 suggest FWHM$_{stars}$ in the range $\sim$250-900 km s$^{-1}$ (Table 2), consistent with values measured in other type 2 quasars (Bian et al. 2007, Liu et al. 2009) using stellar features.

The velocity shifts $V_S$ of the different [OII] kinematic components relative to the narrow line core will provide additional information to characterize the kinematics.

3 RESULTS

3.1 Integrated line profiles

We show in Table 1 the FWHM of [OIII] and H$\beta$ lines. For an initial, general characterization of these quantities we have applied single Gaussian fits to both lines. The goal of this is to compare with similar studies of type 1 quasars.

The [OIII] FWHM values in Heckman, Miley & Green (1984) subsample of 35 type 1 quasars are in the range [260-850] km s$^{-1}$, with a median value of 460 km s$^{-1}$. If only the 10 radio quiet quasars are considered the range is the same, but the median value increases to 570 km s$^{-1}$. The range in our sample is [410±10 to 1860±20] km s$^{-1}$ and the median is 510 km s$^{-1}$.

A visual inspection of the [OIII] spectral profiles reveals that it is asymmetric in the majority of objects. Following Heckman et al. (1983), we have quantified the degree of asymmetry at 10%, 20% and 50% of the line maximum intensity using the parameters AI10, AI20 and AI50. AI10 is defined as $WL_{10}/WR_{10}$, where WL10 and WR10 are the half widths to the left and right of the center of the narrow [OIII] core at 10% intensity level. The widths were corrected for instrumental broadening. AI20 and AI50 are defined in the same way, but at 20% and 50% intensity levels respectively. AI10 is introduced compared with previous studies (see also Spoon & Holt 2010) because we find that in most objects the asymmetry is perceived at very low intensity levels, in the form of faint wings. The schematic representation of the various parameters involved in these calculations is shown in Fig. 15. The half widths WL10, WR10, etc have a “+” because they correspond to values not corrected for instrumental broadening.

AI10, AI20 and AI50 are shown in Table 1. Positive, negative and 0 values indicate blue (highlighted in bold), red (italic fonts) and no asymmetries (normal fonts) respectively. It can be seen that the fraction of asymmetric profiles increases at lower intensity levels (7/13 at 50%; 9/13 at 20% and 10/13 at 10% levels). While at 50% level there is a variety of asymmetries with no clear preference for a given sign,

1 Type 2 quasars are most frequently associated with elliptical galaxies (Mainieri et al. 2011, Zakamska et al. 2006), so random motions are possible.
at lower intensity blue asymmetries become predominant: at 10% level 9/13 objects show a blue asymmetry, vs. 2 with red and 2 more which no asymmetry. Our results are consistent with Heckman, Miley & Green (1984), who found a clear predominance of blue asymmetric [OIII] profiles in radio quiet and flat steep spectrum (compact) radio loud quasars at z \( \leq 0.5 \). The asymmetries disappear in steep spectrum (extended) radio loud objects. None of the objects in our sample are radio loud.

An excess of blue asymmetries suggests that a significant fraction of the line emitting gas is moving radially in an outflow (see \( \delta 1 \)).

3.2 Spectral decomposition of the H\( \beta \)-[OIII] line profiles.

The [OIII] spectral line profiles show complex kinematic substructure in all 13 objects: 3 kinematic components are required to produce the best fit in 8/13 objects, while 2 are required for the remaining 5 (Fig. 1 to 13).

All quasars in our sample have one or two kinematic components with [OIII] FWHM \( \lesssim \)FWHM_{stars} (Table 2), i.e., they show no sign of kinematic disturbance. The presence of two components which seem to follow gravitational motions is not surprising, since the emissions from the NLR (probably dominant) and possibly also the EELR are expected within the spatial apertures used to extract the spectra. According to studies of narrow line radio galaxies, the EELR is expected to have different kinematic, physical and ionization properties than the NLR (e.g. Tadhunter, Fosbury & Quinn 1989, Robinson et al. 1987).

All objects show, moreover, a very broad component with [OIII] FWHM \( \gtrsim \)2×FWHM_{stars}. In general, this component is broader than the maximum possible value of FWHM_{stars} allowed by Greene & Ho (2003) correlation scatter (see \( \delta 2.2 \)). Therefore, the uncertainty on FWHM_{stars} does not affect our conclusion. Thus, the NLR of all type 2 quasars in our sample contains highly perturbed gas, in addition to the more quiescent, ambient gas whose FWHM is consistent with gravitational motions.

The FWHM of the perturbed gas components are in the range 780±30 to 2500±200 km s\(^{-1}\) with a median value of 1280 km s\(^{-1}\). Their velocity shifts relative to the [OIII] narrow core \( V_S \) are in the range 10±40 and up to \( \sim 620\pm 140 \)

| Object     | z    | FWHM [OIII] | FWHM H\( \beta \) | FWHM_{core} | AI10 | AI20 | AI50 |
|------------|------|-------------|------------------|-------------|------|------|------|
| SDSS J2358-00 | 0.402 | 440±50      | 420±85           | 430±10      | 0.03±0.04 | 0.00±0.03 | 0.00±0.03 |
| SDSS J0025-10  | 0.303 | 435±55      | 420±70           | 320±80      | 0.33±0.05 | 0.36±0.08 | 0.42±0.09 |
| SDSS J0123+00  | 0.399 | 445±45      | 470±60           | 430±50      | 0.10±0.05 | 0.07±0.07 | 0.04±0.06 |
| SDSS J0217-00  | 0.344 | 910±30      | 700±60           | 700±60      | 0.22±0.03 | 0.06±0.04 | -0.17±0.09 |
| SDSS J0234-07  | 0.310 | 510±60      | 420±60           | 450±50      | 0.39±0.04 | 0.32±0.05 | 0.53±0.09 |
| SDSS J0955-03  | 0.422 | 1320±30     | N/A              | 940±60      | 0.13±0.03 | 0.14±0.07 | -0.15±0.09 |
| SDSS J1153+03  | 0.575 | 550±10      | N/A              | 440±20      | -0.05±0.06 | -0.05±0.04 | -0.06±0.09 |
| SDSS J1228+00  | 0.575 | 1860±20     | N/A              | 1100±100    | -0.66±0.03 | -0.42±0.04 | -0.45±0.05 |
| SDSS J1307-02  | 0.455 | 410±10      | 455±15           | 360±10      | 0.15±0.03 | -0.10±0.05 | 0.00±0.04 |
| SDSS J1337-01  | 0.329 | 900±30      | N/A              | 540±50      | 0.33±0.07 | 0.19±0.07 | 0.15±0.06 |
| SDSS J1407+02  | 0.309 | 430±20      | 460±15           | 400±10      | 0.18±0.06 | 0.17±0.09 | 0.20±0.10 |
| SDSS J1413-01  | 0.380 | 550±10      | 570±40           | 500±10      | 0.03±0.04 | 0.03±0.03 | 0.00±0.03 |
| SDSS J1546-01  | 0.383 | 500±40      | 440±30           | 430±20      | 0.39±0.08 | 0.43±0.08 | 0.00±0.05 |

Table 1. Type 2 quasar sample studied in this work with kinematic measurements based on single Gaussian fits to the [OIII] and H\( \beta \) lines. The redshift is shown in column (2). The [OIII] and H\( \beta \) FWHM are in columns (3) and (4). Column (5) gives the FWHM of the narrow [OIII] core that remains after the asymmetric line wings are removed. AI10, AI20 and AI50 in columns (6), (7) and (8) quantify the degree of asymmetry of the [OIII] line profile at 10%, 20% and 50% intensity levels respectively. Positive, negative and zero values (taking errors into account) correspond to blue, red and no asymmetries, which are highlighted in bold, italic and normal fonts respectively.
We have plotted $R = \frac{FWHM_{[OIII]}}{FWHM_{\text{stars}}}$ vs. $V_S$ for all kinematic components (Fig. 16). The two objects highlighted in colour are SDSS J1153+03 (orange) and SDSS J1228+00 (green). Villar-Martín et al. (2011) proposed that these quasars might have an intermediate orientation between type 1 and type 2, so that we have a direct view of an intermediate density region, more interior and closer to the black hole than the NLR we see in the rest of the sample. Fig. 16 shows that they are also peculiar from the kinematic point of view, since they are the only ones showing kinematic components with large red velocity shifts.

If these two peculiar objects are excluded, Fig. 16 shows a strong trend for the highly perturbed gas (i.e. kinematic components with $R \geq 2$) to be blueshifted, while the more quiescent gas (components with $R \lesssim 1.0$) shows in general no or small velocity shifts.

$V_S$ is plotted vs. the FWFHM in Fig. 17 for the individual kinematic components isolated in each quasar. Selecting a given symbol, it can be seen that the largest FWHM values (i.e. the most perturbed gas in a given object) are in general associated with the largest blueshifts. This result is found in all objects where the velocity uncertainties allowed a definitive conclusion (7/11).

Thus, the perturbed gas shows both broad FWHM compared with the stellar velocity dispersion and a trend to show the largest blueshift. The perturbed gas is therefore responsible for the blue line profile asymmetries. All together suggest the presence of ionized gas outflows in the inner \( \lesssim \)few kpc, such that the receiding gas is obscured by dust.

The relative contribution of the perturbed (i.e. outflowing) gas to the total [OIII] line flux \( R_2 = \frac{FWHM_{[OIII]}^\text{out}}{FWHM_{[OIII]}^\text{tot}} \) (column 5 in Table 2) varies strongly from object to object. It can account for \( \sim \)10% and up to \( \sim \)70% of the total line flux. An anticorrelation is observed. Kinematic components with more extreme kinematics (larger $R$) have a smaller relative contribution to the total line flux.

The perturbed gas is also detected in Hβ in 7 objects. The [OIII]/Hβ ratio is in general very high (\( \geq 10 \)), in most cases where it could be measured, which is similar or even
larger than that of the narrower kinematic components. This suggests very high excitation level of the outflowing gas.

Given the size of the apertures used to extract the spectra, the effects of the outflows we see are constrained within radial spatial scales of \( r \lesssim \text{few kpc} \) from the central engine. Larger spatial scales of the total outflowing region are not discarded (e.g. Humphrey et al. 2011).

4 DISCUSSION

4.1 Outflows in the NLR of type 2 quasars.

We have found evidence for outflows of ionized gas in the central regions (\( r \lesssim \text{few kpc} \)) of most type 2 quasars in our sample (11/13). Six objects in the sample were selected on the basis (among other things) of prior evidence of nuclear kinematic perturbation (Villar-Martín et al. 2011) such as broad and/or highly asymmetric [OIII] lines. However, not obvious bias was applied to give preference to blue vs. red asymmetries. Moreover, six out of the seven objects for which kinematic criteria were not applied also contain outflows. So, in spite of the apparent selection bias, the results suggest that the outflow phenomenon is common in the NLR of type 2 quasars. This is consistent with Heckman, Miley & Green (1984), who found similar evidence in the NLR of the majority of radio quiet type 1 quasars (see also Leipski & Bennert 2006).

The outflowing gas shows high ionization level with [OIII]/H\( \beta \) sometimes \( \gtrsim 10 \), and often similar or larger than the more quiescent gas. A similar result has been found in some radio quiet type 1 quasars (e.g. Leipski & Bennert 2006) and Seyfert galaxies (Veilleux 1991). Independently of the outflow origin, such high excitation suggests that stars are not responsible for ionizing the outflowing gas, but rather AGN related phenomena. This supports that the outflows are within the quasar ionization cones, as commented above. Although contribution from the EELR is expected in the spectra of at least some objects, the line emission is likely to be dominated by the NLR so that the outflows are expected to be located in this region.

The outflowing gas emits very broad lines (FWHM\( \gtrsim 2\times \text{FWHM}_{\text{stars}} \)), with FWHM in the range 780±30 to 2500±200 km s\(^{-1} \)) and projected shifts relative to the systemic velocity in the range \( V_S \sim 10\pm40 \) and up to \( \sim 620\pm140 \) km s\(^{-1} \) relative to the systemic velocity. The \( V_S \) are in general much less extreme than the motions implied by the large FWHM. Very broad lines can be produced by acceleration of clouds by or behind the bow shock generated by the outflow (e.g. Villar-Martín et al. 1999). Also, it must be taken into account that the deperturbed velocity shifts are likely to be larger, since these are type 2 objects and the cones axis is close to the plane of the sky.

We have found a anticorrelation such that the strongest the kinematic perturbation (larger \( R \)), the lowest the relative contribution of the outflowing gas to the total [OIII] line (smaller \( R^2 \)). Since there is no obvious change in the ionization level of the outflowing gas relative to the ambient, non perturbed gas, this anticorrelation possibly reflects that, the more perturbed the gas is, the smaller the gas mass fraction the outflow involves.

Based on the spatially resolved behaviour of the FWHM and \( V_S \) of [OIII] line in a sample of 15 type 2 quasars at 0.11\( \lesssim z \lesssim 0.43 \), Greene et al. (2011) also proposed that outflows of ionized gas are present in their sample.

4.2 Outflow mass and mass outflow rate

The mass of the ionized outflowing gas \( M \) can be estimated with:

\[
M = \frac{1.4 \, m_p \, L(H\beta)}{n_e \, h \nu H\beta \, \alpha_{H\beta}^{\text{eff}}}
\]

where \( L(H\beta) \) is the luminosity of the broad H\( \beta \) component, \( n_e \) the density of the outflowing gas, \( m_p \) the proton mass, \( \alpha_{H\beta}^{\text{eff}} \) the effective H recombination coefficient for H\( \beta \) (Osterbrock 1989) and \( h \nu H\beta \) is the energy of an H\( \beta \) photon.

This refers to the outflowing gas detected within the slit. If the outflows are constrained to a region of size \( r \lesssim \text{few kpc} \), we expect \( M \) to provide an adequate measurement of the total outflowing gas, otherwise (e.g. Humphrey et al. 2011) the inferred masses are lower limits.

Large uncertainties affect this calculation since the unreddened H\( \beta \) luminosity is unknown and we have no density measurements. The spectral fits imply observed L(H\( \beta \)) in the range (0.2-2,1)\( \times 10^{41} \) erg s\(^{-1} \) for an illustrative comparison, the masses involved in the outflowing gas cover a broad range from \( \sim \text{several hundred cm}^{-3} \) (e.g Villar-Martín et al. 1999, Arribas & Mediavilla 1986, Villar-Martín et al. 1999, Heckman, Miley & Armus 1990) to \( n_e > 10^4\)\( \text{cm}^{-3} \) (Axon et al. 1998), \( n = 250 \text{ cm}^{-3} \) seems therefore a reasonable lower limit. Thus, we assume a range of densities \( n \sim 250 - 3000 \text{ cm}^{-3} \) for the outflowing gas. The implied values for \( M \) using the uncorrected L(H\( \beta \)) are in the range \( \sim (0.3-1.5)\times 10^5 \) M\(_\odot \) for \( n \sim 250 \text{ cm}^{-3} \) and depending on the object. The values are 120 times lower for \( n \sim 3000 \text{ cm}^{-3} \) (Greene et al. 2011) propose \( \sim 10^7 \) M\(_\odot \) as a strict lower limit assuming a gas density \( \sim \text{few cm}^{-3} \). It must be taken into account that these authors argue that all the H\( \beta \) emitting gas is involved in the outflow (we find this is not the case), and that much lower densities are possible.

For an illustrative comparison, the masses involved in neutral and molecular outflows in Seyfert and ultraluminous infrared galaxies (ULIRGs), which are constrained to spatial scales of \( \lesssim \text{few kpc} \), are \( > 10^9 \) M\(_\odot \), and often \( > 10^{10} \) M\(_\odot \) (e.g. Rupke, Veilleux & Sanders 2005, Sturm et al. 2011).

It is obvious that better constraints on the intrinsic L(H\( \beta \)) and density of the outflowing gas are essential to obtain more tightly constrained masses. It is also essential to investigate the existence of outflows in other gas phases. Indeed, outflow studies in different types of galaxies suggest that the ionized phase reveals a very small fraction of the total outflowing mass, which is likely to be dominated by...
Table 2. Results of the spectral decomposition analysis of [OII] and Hβ. (1): Object (shortened) name. (2): Sign of the [OII] profile asymmetry implied by AI10 (Table 1). (3) Flux in units of $10^{-16}$ erg s$^{-1}$ cm$^{-2}$. (4) Fractional contribution of a given kinematic component to the total [OII] flux. (5) Idem for Hβ. (6) Ionization level as measured from the [OII]/Hβ ratio. (7) FWHM. (8) Velocity shift $V$ relative to the [OII] narrow core. (9) [OII]/Hβ calculated with the total line fluxes (rather than the individual kinematic components as in (6)). (10) Total [OII] luminosity in units of $10^{42}$ erg s$^{-1}$. (11) Stellar velocity dispersion calculated according to FWHM([OII]$_{\text{core}}$)=1.24±0.76$\times$FWHM$_{\text{stars}}$ (Greene & Ho 2005). The errors do not account for the scatter of the correlation (see 13.2).

The molecular and neutral phases. As an example, the mass of ionized gas in the (galactic) superwind region of the M82 is generated, since most of the outflowing gas should be heated as observed in some galactic scale outflows (Walter, Heckman & Miley 1994; Lehnhert & Heckman 1996; Rupke et al. 2002). Let us consider a scenario which favours the efficiency of the outflows to constrain the mass outflow rates.

More restrictive conditions are required to produce $M>50$ M$_\odot$ yr$^{-1}$ as observed in some galactic scale outflows powered by active star formation (e.g. Heckman, Armus & Miley 1996; Heinz & Heckman 1996; Rupke et al. 2002). Let us consider a scenario which favours the efficiency of the outflow: low densities ($n_e=250$ cm$^{-3}$) and large line luminosity corrections (e.g. intrinsic L(Hβ)≈10$^8$ observed L(Hβ)). With these favourable prerequisites, the size of the outflowing region must be $r < < 1$kpc. Studies of ionized gas outflows using UV and X ray absorption lines indicate that such small distances relative to the continuum source are possible. If the outflow region has $r < < 1$kpc, the mass outflow rate is generated, since most of the outflowing gas should becolmated within a very narrow cone near the plane of the sky for all objects.

It is clearly essential to determine the location of the outflows to constrain the mass outflow rates.

Table 2. Results of the spectral decomposition analysis of [OII] and Hβ. (1): Object (shortened) name. (2): Sign of the [OII] profile asymmetry implied by AI10 (Table 1). (3) Flux in units of $10^{-16}$ erg s$^{-1}$ cm$^{-2}$. (4) Fractional contribution of a given kinematic component to the total [OII] flux. (5) Idem for Hβ. (6) Ionization level as measured from the [OII]/Hβ ratio. (7) FWHM. (8) Velocity shift $V$ relative to the [OII] narrow core. (9) [OII]/Hβ calculated with the total line fluxes (rather than the individual kinematic components as in (6)). (10) Total [OII] luminosity in units of $10^{42}$ erg s$^{-1}$. (11) Stellar velocity dispersion calculated according to FWHM([OII]$_{\text{core}}$)=1.24±0.76$\times$FWHM$_{\text{stars}}$ (Greene & Ho 2005). The errors do not account for the scatter of the correlation (see 13.2).

The molecular and neutral phases. As an example, the mass of ionized gas in the (galactic) superwind region of the M82 starburst galaxy is $2\times10^8$ M$_\odot$ (Heckman, Armus & Miley 1994), while the molecular mass involved in the outflow is $3\times10^8$ M$_\odot$ (Walter, Weiss & Scoville 2002). The mass outflow rate $M$ can be calculated as (Dopita & Sutherland 2003):

$$M = \frac{3}{4\pi} \frac{v_o}{r} \frac{L(H\beta)}{m_p} = \frac{2.1 \frac{v_o}{r}}{M}$$

Assuming a spherical geometry, $v_o$ is the expanding velocity of the outflowing bubble and $r$ its radius. In addition to those affecting $M$, additional uncertainties are involved for $v_o$, which is likely to be $>v_e$ (Table 2) and $r$. Although different works suggest that the radius of the NLR in quasars is $<5$ kpc (e.g. Bennett et al. 2002, Greene et al. 2011), this is only an upper limit for $r$, since the size of the outflowing region could be smaller.

In spite of the uncertainties, it is interesting to study the conditions which are required to produce different $M$. For instance, mass flow rates of the NLR outflows discovered in Seyfert and nearby narrow line radio galaxies are typically $<5$ M$_\odot$ yr$^{-1}$ (Rupke, Veilleux & Sanders 2004). Heckman et al. 1983; see also Humphrey et al. 2010). Such values are certainly possible in our sample within a rather broad range of allowed parameter values.
5 CONCLUSIONS

We have analyzed the spatially integrated kinematic properties of the NLR gas in a sample of 13 optically selected SDSS type 2 quasars at $z \sim 0.3-0.6$ using the [OIII]λλ4959,5007 lines. Optical long-slit spectroscopy at moderate spectral resolution $R \sim 900-1300$ obtained with FORS2 on the VLT has been used for this purpose.

The line profiles show a significant asymmetry in 11 of the 13 quasars. There is a clear preference for blue asymmetries, which are found in 9/13 objects. An excess of blue line asymmetries have been observed in other active classes and objects. All together support that the perturbed gas, which is outflowing gas in the range 780–1300 obtained with FORS2 on the VLT

We propose the same interpretation. The outflows we see are constrained within spatial scales of $r < \text{few kpc}$ from the central engine.

This scenario is favoured by other results we find: in addition to more quiescent gas, whose kinematic properties are consistent with gravitational motions, we have discovered highly perturbed gas in all objects. This gas emits very broad lines ($R = \frac{\text{FWHM}}{\lambda \lambda 4959,5007} \gtrsim 2$). While the quiescent gas shows small or null velocity shifts relative to the systemic velocity, the highly perturbed gas trends to show larger shifts. These, moreover, are blueshifts in general. In each object the most perturbed gas trends to have the largest blueshift as well. All together support that the perturbed gas, which is responsible for the blue asymmetries on the line profiles, is outflowing.

The projected velocity shifts relative to the narrow core of the [OIII] line, which we have considered a reasonable tracer of the systemic velocity, are in the range $10 \pm 40$ and up to $\sim 620 \pm 140 \text{ km s}^{-1}$, with a median value of $\sim 145 \text{ km s}^{-1}$. The intrinsic expanding velocities are likely to be larger, given the orientation of the objects. We FWHM for the outflowing gas in the range $780 \pm 30$ to $2500 \pm 200 \text{ km s}^{-1}$ with a median value of $1280 \text{ km s}^{-1}$. The relative contribution of the outflowing gas to the total [OIII] line flux varies from object to object in the range $\sim 10-70\%$. An anticorrelation is found such that, the more perturbed the outflowing gas is (larger $R$), the lower its relative contribution is to the total [OIII] flux. Our results suggest that outflows with more perturbed kinematics involve a smaller fraction of the total mass of ionized gas.

The outflowing gas is in general very highly ionized, as suggested by the large [OIII]/Hβ values (often $>10$). Independently of the outflows origin, this suggests that the gas is ionized by the quasar, rather than stars, an therefore it is located within the quasar ionization cones.

We argue that our results suggest that nuclear dusty outflows are a common phenomenon in optically selected type 2 quasars at $0.3 < z < 0.6$.

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