Deconstructing the narrow-line region of the nearest obscured quasar

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ABSTRACT
We study the physical and kinematic properties of the narrow line region (NLR) of the nearest obscured quasar MRK 477 (z=0.037), using optical and near-infrared (NIR) spectroscopy. About 100 emission lines are identified in the optical+NIR spectrum (90 in the optical), including several narrow optical Fe+ lines. To our knowledge, this is the first type 2 active galactic nucleus (AGN) with such a detection. The Fe+ lines can be explained as the natural emission from the NLR photoionized by the AGN. Coronal line emission can only be confirmed in the NIR spectrum.

As in many other AGN, a significant correlation is found between the lines full width at half-maximum and the critical density log(n crit). We propose that it is caused by the outflow. This could be the case in other AGNs.

The nuclear jet-induced ionized outflow has been kinematically isolated in many emission lines covering a broad range of ionization potentials and critical densities. It is concentrated within R ~few×100 pc from the central engine. The outflowing gas is denser (n >8 000 cm⁻³) than the ambient non-perturbed gas (n ~400-630 cm⁻³). This could be due to the compression effect of the jet induced shocks. Alternatively, we propose that the outflow has been triggered by the jet at R ~<200 pc (possibly at ~<30 pc) and we trace how the impact weakens as it propagates outwards following the radiation-pressure dominated density gradient.

The different kinematic behaviour of [FeII] λ1.644 μm suggests that its emission is enhanced by shocks induced by the nuclear outflow/jet and is preferentially emitted at a different, less reddened spatial location.

Key words: galaxies: active quasars: emission lines - quasars: general - quasars: individual: MRK 477

1 INTRODUCTION
MRK 477 (SDSS J144038.1+533016, z=0.037 and luminosity distance D_L=161 Mpc) is a type 2 luminous active galactic nucleus (AGN). Also known as I Zw 92, it was first identified by Zwicky (1966) as a compact galaxy. It is usually referred to as the most luminous Seyfert 2 in the local Universe. As pointed out by Heckman et al. (1997), it has the highest [O III]λ5007 luminosity (L_{[OIII]}=3.3×10^{42} erg s⁻¹) of any of the 140 Seyfert nuclei (type 1 or 2) compiled by Whittle (1992) and the fifth highest radio power (P_{1.4GHz} =2.0×10^{30} erg s⁻¹ Hz⁻¹ at 1.4 GHz). Indeed, its high L_{[OIII]} places it in the regime of optically selected obscured quasars (QSO2), according to the selection criteria defined by Zakamska et al. (2003). L_{[OIII]} >1.2×10^{42} erg s⁻¹. The [OIII] luminosity implies a bolometric luminosity L_{bol}=8.6×10^{45} erg s⁻¹ (Stern & Laor 2012, see also Lamasstra et al. 2004), which is in the quasar range (Shen et al. 2011).
The quasar host galaxy is interacting with an emission line companion, possibly a LINER, located 50 arcsec (∼36 kpc) to the north (De Robertis et al. 1997). Hubble Space Telescope (HST) images are shown in Fig. [1]. Both galaxies are connected by a faint bridge and prominent tidal tails are apparent. The ratio of stellar masses between the quasar host and the companion is M1/M2=1.6 (Koss et al. 2012).

The quasar host shows a compact blue central source, peculiar among type 2 AGNs, but no evidence for a broad line region (BLR), prompting some authors to suggest that the quasar lacks one. However, polarization observations have revealed a hidden BLR (e.g. Tran et al. 1992; Tran et al. 1994; Shu et al. 2007). The nuclear continuum polarization is ≤1.5%, significantly lower than that of the broad lines, implying that the majority of the optical continuum cannot be due to scattered light from the hidden type 1 nucleus. The blue central source is instead associated with a compact dusty starburst (effective radius<0.2 kpc) which occurred ~6 Myr ago in a brief period of time and whose light dominates from the ultraviolet to the near-infrared (NIR; Heckman et al. 1997). This is therefore a starburst-AGN hybrid system. MRK 477 has a star-forming rate SFR=24 M⊙ yr−1 inferred from the infrared (IR) luminosity (assuming that it is starburst-dominated) log(LIR/Myr)=11.14 (Krug et al. 2010). This places it in the regime of luminous IR galaxies (LIRGs: 11≤log(LIR/Myr)<12). The detection of the Wolf-Rayet (WR) blue bump around the He II λ4686 line by Heckman et al. (1997) led these authors to propose that MRK 477 is a luminous member of the class of WR galaxies.

The QSO2 host harbors a supermassive black hole with a mass in the range log(MBH)~7.18 (as derived from the MBH versus σcorrelation) to 8.84 (as inferred from the polarimetric Hβ line; Zhang, Bian & Huang 2008).

Although radio quiet according to the L(OIII) versus Lradio, radio loud versus radio quiet, classification criteria (explained in Villar-Martín et al. 2014), MRK 477 shows a clear excess of radio emission compared to that expected from the stellar contribution. The 8.4 GHz Very Large Array (VLA) radio continuum map (0.26 arcsec resolution) shows a triple radio source (~1.2 arcsec total extension) whose morphology correlates with that of the narrow line region (NLR). The size and overall northeast-southwest axis of the radio structures are shared by the [OIII] emission, which extends up to a similar distance to the north-east (Heckman et al. 1987).

Shuder & Osterbrock (1981) reported for the first time that the emission lines have a large blue-ward asymmetry (i.e., excess) at low intensity level relative to the continuum. Villar-Martín et al. (2014) proposed that the ionized nuclear outflow responsible for such an asymmetry has been triggered by the interaction between the radio source and the NLR. These authors proposed that negative feedback can be triggered by the radio structures in a significant fraction of radio quiet quasars. Thanks to its high intrinsic luminosity and closeness, MRK 477 is an excellent test object to gain further insight into this mechanism.

We present here a detailed study of the optical and near-infrared spectra of MRK 477. We explore a diversity of aspects that provide a more complete understanding of the nature of this object, example of a type 2 quasar in the nearby universe, as well as a starburst-AGN hybrid system. The paper is organized as follows. The spectra are described in Sect. 2, together with the spectral fitting procedure. We present results in Sect. 3 regarding line identification, correlations between the gas kinematics and a diversity of parameters (ionization potential, critical density), the spatial extension of the ionized gas, the ionized outflow, the presence of narrow Fe+ emission lines, the coronal line spectrum and the detection of WR features. The results are discussed in Sect. 4 and the conclusions are presented in Sect. 5.

2 DATA SET

2.1 Optical spectrum

The optical spectrum was obtained as part of the Sloan Digital Sky Survey (SDSS, York et al. 2000). It spans the rest frame range ∼3660–8880 Å range (Figs. 2 and 3). It corresponds to an aperture defined by the 3 arcsec diameter SDSS fibre (∼2.2 kpc at z =0.037) centred at the galaxy nucleus. For comparison, the triple radio source identified by Heckman et al. (1997) has a total extension of ∼1.2 arcsec and thus it is well within the fibre area.

The spectral resolution is ∼180±20 km s−1. All values of emission line full width at half-maximum (FWHM) have been corrected for instrumental broadening.

The main emission lines have large equivalent widths and the stellar features are comparatively weak. Underlying stellar absorption of the Balmer lines is expected to be negligible and therefore subtracting the stellar continuum is not necessary for our purposes.

2.2 NIR spectrum: observations and data reduction

NIR H+K long-slit spectra were obtained with the NIR camera/spectrometer LIRIS (Long-slit Intermediate Resolution Infrared Spectrograph; Acosta-Pulido et al. 2002; Manchado et al. 2004), attached to the Cassegrain focus of the 4.2 m William Herschel Telescope (WHT). LIRIS is equipped with a Rockwell Hawaii 1024×1024 HgCdTe array detector, whose spatial scale is 0.25 arcsec pixel−1.

The NIR observations were performed as part of the Isaac Newton Group service programme (programme SW2014b22) in two different nights, 28 March 2015 and 02 May 2015. The H+K grism was used. It covers the 1.388–2.2 ˚A m spectral range and provides a dispersion of 9.7 ˚A pix−1. The seeing size during the March observations was FWHM~2” (as measured from the standard star). A 1” wide slit was used oriented at position angle PA=43° East of North. This PA is aligned with the radio axis and the NLR axis as seen in the HST image presented by Heckman et al. (1997). The resulting spectral resolution was 35.7±2.2 Å (or...
Figure 1. Hubble Space Telescope (HST) images of MRK 477. They were obtained with Wide-Field Planetary Camera 2 (WFPC2, F606W filter, left), the Advanced Camera for Surveys (ACS/HRC, F330W filter, middle) and the near-infrared Camera and Multi-Object Spectrometer (NICMOS, F160W filter, right) respectively. The flux intensity maps are represented in logarithmic scale such that \( F \, [\text{erg} \, s^{-2} \, \text{cm}^{-2} \, \text{A}^{-1} \, \text{arcsec}^{-2}] = 10^{A+b} \), where \( A \) is a constant factor (i.e., \(-18.3\), \(-14.5\) and \(-16.4\), respectively, for WFPC2, ACS and NICMOS images) and \( b \) is indicated in the coloured bar. The white box in the WFPC2 image identifies the FoV covered by the ACS and NICMOS images. The horizontal line at the bottom left of these images corresponds to a scale of 10 kpc for the WFPC2 image and to a scale of 2 kpc for the ACS and NICMOS images. The spatial scale for this galaxy is 0.725 kpc arcsec. North is at the top and East to the left in all the panels.

550±34 km s\(^{-1}\) at the observed wavelength of \( \lambda \alpha \)). In Fig. 2 we show the NIR spectrum extracted from a 3.5″ aperture, centred at the position of the nucleus. The total exposure time on source was 6400 s (16×400 s).

The May data were obtained with seeing \( FWHM=0.65±0.05″ \) (measured from the standard star). A 0.75″ slit was used, also with \( PA=43° \). The resulting spectral resolution was 23.2±1.2 A (or 318±18 km s\(^{-1}\)) . The observations were performed through clouds and the signal to noise ratio of the final spectrum was low. In spite of this, the good seeing conditions allowed to obtain more accurate information on the spatial extension of the strongest emission line \( \lambda \alpha \). The total exposure time on source was 4000 s (10×400 s). All FWHM values of the NIR spectra have been corrected for instrumental broadening.

The data were reduced following standard procedures for near-IR spectroscopy, using the LIRISDR dedicated software within the IRAF\(^2\) environment. For a detailed description of the reduction process see Ramos Almeida et al. (2009). Consecutive pairs of AB two-dimensional spectra were subtracted to remove the sky background. The resulting frames were then wavelength calibrated and flat-fielded before registering and co-adding all frames to provide the final spectra.

The absolute flux calibration of the March spectrum is intended to be an approximation since the spectra of the NLR of the nearest obscured quasar \( \sim \) \( \lambda \lambda 4959,5007 \) (same number of kinematic components with identical FWHM in km s\(^{-1}\) and relative velocities, as explained in Villar Martín et al. [2014]). In physical terms, this method corresponds to a situation where all gaseous regions emit all lines, although with different relative fluxes.

2 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for the Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation [http://iraf.noao.edu/].

2.3 Spectral fitting

In order to study the kinematic and physical properties of the nuclear ionized outflow we have fitted the spectral profiles of numerous emission lines (Sect. 3). For this we used the STARLINK package DIPSO. This software is based on the optimization of fit coefficients, in the sense of minimizing the sum of the squares of the deviations of the fit from the spectrum data. The output from a completed fit consists of the optimized parameters (Gaussian central \( \lambda \), FWHM, intensity peak, flux) and their errors (calculated in the linear approximation, from the error matrix).

Two methods were attempted. Method I, we assumed that all emission lines have the same kinematic substructure as \( \lambda \lambda 4959,5007 \) (same number of kinematic components with identical FWHM in km s\(^{-1}\) and relative velocities, as explained in Villar Martín et al. [2014]). In physical terms, this method corresponds to a situation where all gaseous regions emit all lines, although with different relative fluxes.

On the other hand, this is not necessarily the case and some lines might come from different regions, possibly resulting in variations of the kinematic substructure from line to line. As an example, low critical density lines (\( \sim \) few×10\(^3\) cm\(^{-3}\)) are quenched in high density gas with \( n > 10^8 \) cm\(^{-3}\). To account for this possibility, whenever possible we have also attempted to fit the lines without applying prior kinematic restrictions (method II).

Also, all fits that produced unphysical results were rejected even if mathematically valid (e.g. a fit producing [NII] \( \lambda 6583 \approx 30 \) very different from the theoretical value 3.0).

As we will see the lines are complex with multiple kine-
Figure 2. SDSS spectrum of MRK 477. Flux is given in units of $10^{-13}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ and the rest-frame wavelength is in Å. Some of the strongest emission lines are indicated.

Figure 3. Four zoomed spectral windows covering the full spectral range are shown to highlight some of the weakest lines. Unless otherwise specified, fluxes in these and other figures are given in units of $10^{-14}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$. Some relevant lines are indicated.
matic components and they are often severely blended with neighbour lines so that the fits are sometimes complicated and not unambiguous. Applying methods I and II whenever possible we account for the uncertainties involved in a more realistic way than using a single method.

Both methods do not always produce acceptable results. For instance, the [SII]λ6716,6731 blends could not be successfully fitted applying full constraints from the [OIII] lines. The opposite occurs with the Hα+[NII] blend.

Methods I and II could be successfully applied to Hγ, [OIII]λλ4963, 5007 and [OII]λ3726. It is found that, [OIII]λ4363 is the most uncertain. While the narrow and intermediate components isolated in the fits of the other three lines differ by <20 per cent. These uncertainties will be taken into account when relevant.

3 RESULTS

3.1 Line identification.

We identify ~90 emission lines in the SDSS optical spectrum of MRK 477 (Table 1), many of them detected for the first time in this object. For some features the identification is ambiguous and/or it could be the contribution of several emission lines. In such cases, all the possible identifications or contributors are quoted separated with “+”. As an example, a broad feature with an asymmetric profile is detected at λ ∼ 5272 Å. This is identified as “[Fe III]/[Fe II]/[Fe VII]” because it might be the blend of [Fe II]λ5270.4, [Fe II]λ5273.4,5276.0 and [Fe VII]λ5276.4.

When two or more lines are known to contribute to a given feature, all are quoted and separated with “+.” For instance, the [OII] at λ ∼3727 and [Ni] at λ ∼5200 doublets are shown as “3727.0+3728.8” and “5197.9+5200.4”.

The works by Veron-Cetty, Joly & Veron (2004) and Veron-Cetty et al. (2013) have been used for iron (Fe) line identifications. The critical densities n_{crit} of forbidden transitions are quoted in column 5 of Table 1 when available. Most have been computed with the PYNEB package optimized for the analysis of emission lines (Luridiana, Morisset & Shaw 2013). These have been estimated for T_e ∼15,000 K. The rest have been retrieved from De Robertis & Osterbrock (1984).

The lines identified in the NIR spectrum are shown in Table 2.

3.2 Relationships between the kinematics and n_{crit}, IP_{low} and IP_{high}.

We plot in Fig. 5 the FWHM (top panels) and the velocity shift V_S (bottom) versus the critical density (n_{crit}, Table 1), the lower (IP_{low}) and upper (IP_{high}) ionization potentials for a subsample of ~28 optical and 2 NIR forbidden emission lines. V_S corresponds to the difference between λ_{air} and λ_{obs} in Table 1 where λ_{air} is the vacuum wavelength and λ_{obs} is that measured from the spectrum corrected for z. Only lines for which both parameters could be measured with reasonable accuracy are plotted. As an example, this was not the case for [SIX]λ1.430 and [FeII]λ1.257 due to the weakness of the lines and/or the distortion of the line profiles by sky residuals. The optical and NIR lines span a wide range in critical densities (~1.3×10^4-6.3×10^4 cm^{-3}) and ionization potentials (IP_{high} ~13-205 eV). A significant correlation is found between the FWHM and the critical density (Spearman correlation coefficients r_s=0.79 and p=0.000001, excluding [FeII]λ1.644), as already found by De Robertis & Osterbrock (1986) whose data are shown as open circles. No significant correlation is found with the ionization potentials (r_s=0.43 and p=0.02 for FWHM versus IP_{low} and r_s=0.42 and p=0.03 for FWHM versus IP_{high}). No trends are found either for V_S except maybe an apparent preference for redshifts (V_S >0) for lines with the highest critical densities.

The NIR [FeII]λ1.644 line is a clear outlier in Fig. 5 being too broad compared to what is expected for its critical density (5.6×10^4 cm^{-3}) and ionization potentials (7.9 and 16.2 eV) according to the general trends defined by the other lines. We will discuss this in more detail below.

The correlation between FWHM and n_{crit} has been found in many type 1 and type 2 AGNs and it holds for AGN luminosities that differ by a factor of up to ~5000 (Espey 1994). V_S, on the other hand, shows a different behavior from object to object (e.g. Appenzeller & Ostericher 1985).

The FWHM versus n_{crit} correlation implies that the line emission from the NLR originates in different subregions under different physical conditions and kinematic properties with a broad density range. Higher critical density lines (many of which have also very high ionization potentials) are broader because they are emitted predominantly by higher density gas.

Figure 4. NIR LIRIS-WHT spectrum of MRK 477 extracted from a ~1”×3.5” aperture centered on the nucleus. The detected lines are indicated. Flux is in units of ×10^{-15} erg s^{-1} cm^{-2} Å^{-1} and λ in μm.
### Table 1. Emission lines identified in the SDSS spectrum of MRK 477. The observed line wavelengths $\lambda_{\text{obs}}$ (column 3) have been determined by fitting a single Gaussian to the emission lines. Errors are quoted when they provide relevant information regarding possible multiple identifications or there is a significant shift between the observed and the air wavelengths (column 2). The line ratios (column 4) are given relative to $H_\beta$, with $F(H_\beta)$=1.0±0.04×10^{-18}$ erg s^{-1} cm^{-2}. They are not corrected for reddening. The critical densities are quoted when available. Superscript $a$ in column (5) indicates that $n_{\text{crit}}$ has been taken from De Robertis & Osterbrock (1984). The other $n_{\text{crit}}$ values have been computed with the PYNEB software (see the text).

| (1) | (2) | (3) | (4) | (5) |
|-----|-----|-----|-----|-----|
| Species | $\lambda_{\text{air}}$ (Å) | $\lambda_{\text{obs}}$ (Å) | $F(\lambda)/F(H_\beta)$ | $n_{\text{crit}}$ (cm^{-3}) |
| (OH) | 3727.0±3728.8 | 3726.9 | 2.26±0.18 | (1.3/4.5)×10^7 |
| [NII] | 6548.3 | 6548.4 | 1.5±0.1 | 1.2×10^5 |
| [OII] | 3727.0 | 3726.9 | 0.35±0.05 | 4.0×10^3 |
| [SII] | 6716.4 | 6716.5 | 0.60±0.03 | 1.5×10^3 |
| [OIII] | 7320.0 | 7320.1 | 0.23±0.01 | 6.4×10^6 |
| [NII] | 6548.1 | 6548.1 | 0.53±0.05 | 6.4×10^6 |
| H$\alpha$ | 6562.8 | 6562.9 | 3.9±0.2 | |
| [NIII] | 6583.5 | 6583.4 | 1.5±0.1 | 1.2×10^5 |
| [NII] | 6548.1 | 6548.1 | 0.53±0.05 | 6.4×10^6 |
| [OII] | 3727.0 | 3726.9 | 0.35±0.05 | 4.0×10^3 |
| [SII] | 6716.4 | 6716.5 | 0.60±0.03 | 1.5×10^3 |
| [OIII] | 7320.0 | 7320.1 | 0.23±0.01 | 6.4×10^6 |
| [NII] | 6548.1 | 6548.1 | 0.53±0.05 | 6.4×10^6 |
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| [SII] | 6716.4 | 6716.5 | 0.60±0.03 | 1.5×10^3 |
| [OIII] | 7320.0 | 7320.1 | 0.23±0.01 | 6.4×10^6 |
| [NII] | 6548.1 | 6548.1 | 0.53±0.05 | 6.4×10^6 |
| H$\alpha$ | 6562.8 | 6562.9 | 3.9±0.2 | |
Table 2. Emission lines identified in the NIR spectrum of of MRK 477 extracted from a ~1 arcsec × 3.5 arcsec aperture centered on the nucleus. (a) $n_{\text{crit}}$ from Rodríguez Ardila et al. (2011). (b) $n_{\text{crit}}$ from Drougados et al. (2010). Fluxes are quoted relative to Brγ, for which $F(\text{Brγ})=(3.0\pm0.3)\times10^{-15}$ erg s$^{-1}$ cm$^{-2}$, although the absolute flux calibration is uncertain (see the text).

| Species | $\lambda_{\text{air}}$ (Å) | $\lambda_{\text{obs}}$ (Å) | $F(\text{Brγ})$ | $n_{\text{crit}}$ (cm$^{-3}$) |
|---------|-----------------|-----------------|-----------------|-----------------------------|
| [Si X]  | 1.4305          | 1.4308          | 0.61±0.10       | $6.3\times10^{8}$(a)        |
| [Fe II] | 1.5339          | 1.5337          | 0.79±0.10       | $4.6\times10^{4}$(b)        |
| [Fe II] | 1.6440          | 1.6435          | 4.5±0.5         | $5.6\times10^{4}$(b)        |
| Paα     | 1.8756          | 1.8746          | 12.6±1.4        |                            |
| H$_2$ 1-0S(3) | 1.9576 | 1.9564          | 0.84±0.10       |                            |
| [Si VI] | 1.9629          | 1.9626          | 0.97±0.12       | $6.3\times10^{8}$(a)        |
| H$_2$ 1-0S(2) | 2.0338 | 2.0329          | 0.20±0.02       |                            |
| HeI     | 2.0587          | 2.0575          | 0.29±0.03       |                            |
| H$_2$ 1-0S(1) | 2.1218 | 2.1206          | 0.63±0.17       |                            |
| Brγ     | 2.1661          | 2.1650          | 1.00±0.15       |                            |

Figure 5. The FWHM (top panels) and the velocity shift $V_s$ (bottom panels) of a subsample of ~30 forbidden lines are plotted against the critical density ($\log(n_{\text{crit}})$), the lower and higher ionization potentials of the species involved. The measurements from De Robertis & Osterbrock (1982, dR & Ost 86) are also shown in the top-left panel as open circles. The outlier at $\log(n_{\text{crit}})\sim3.1$ and FWHM~500 km s$^{-1}$ corresponds to [OII]λ3727, which appears artificially broader due to blended doublet components. The NIR lines are marked with red triangles. [FeII]λ1.644 is a clear outlier in the top panels. It is too broad compared to what is expected from the general trend defined by the rest of the lines.
regimes. The $S$/$I$ ratio ($T$ and $Ar IV$ diagnostic line ratios $S$/$I$) is isolated in all cases, including a broad blueshifted component in the spectrum of MRK 477. Three kinematic components are results of the spectral decomposition of the main lines.

| Comp. | FWHM (km s$^{-1}$) | $V_S$ (km s$^{-1}$) | $F_\alpha$ ($\times 10^{-6}$) |
|-------|------------------|------------------|-----------------|
| [SII] | A4068            |                  |                 |
| Narrow | 92±37            | 92±37            | 0.07±0.01       |
| Inter. | 505±35           | 17±10            | 0.26±0.02       |
| Broad  | 1534±97          | -376±26          | 0.25±0.05       |
| [SII] | A4079            |                  |                 |
| Narrow | 92±37            | 92±37            | 0.010±0.006     |
| Inter. | 505±35           | 17±10            | 0.12±0.02       |
| Broad  | 1534±97          | -376±26          | 0.08±0.07       |
| H$\beta$ |                |                  |                 |
| Narrow | 94±37            | 94±37            | 0.23±0.04       |
| Inter. | 505±35           | 17±10            | 0.22±0.06       |
| Broad  | 1534±97          | -376±26          | 0.26±0.03       |
| H$\gamma$ |               |                  |                 |
| Narrow | 157±28           | -7±7             | 0.47±0.03       |
| Inter. | 529±20           | 38±10            | 0.38±0.04       |
| Broad  | 1830±133         | -224±21          | 0.57±0.06       |
| [OIII] | A4363            |                  |                 |
| Narrow | 157±28           | -7±7             | 0.11±0.02       |
| Inter. | 529±20           | 38±10            | 0.43±0.03       |
| Broad  | 1830±133         | -224±21          | 0.27±0.08       |
| [Cl III] |                |                  |                 |
| Narrow | 137±22           | -2±6             | (1.2±0.4)×10$^{-14}$ |
| Inter. | 471±22           | 7±7              | (3.7±0.1)×10$^{-14}$ |
| Broad  | 1032±75          | -188±24          | (2.3±0.1)×10$^{-14}$ |
| [OIII] | A4300            |                  |                 |
| Narrow | 177±15           | 5±9              | 8.5±0.9         |
| Inter. | 545±15           | 22±11            | 13.1±0.5        |
| Broad  | 1839±33          | -227±23          | 9.6±0.7         |
| H$\alpha$ |               |                  |                 |
| Narrow | As [O III] As [O III] | 3.1±0.3 |               |
| Inter. | As [O III] As [O III] | 4.9±0.2 |               |
| Broad  | As [O III] As [O III] | 4.2±0.3 |               |
| [NII] | A6583            |                  |                 |
| Narrow | As [O III] As [O III] | 1.0±0.1 |               |
| Inter. | As [O III] As [O III] | 1.7±0.07|               |
| Broad  | As [O III] As [O III] | 0.9±0.2 |               |
| [Ar IV] | A6716            |                  |                 |
| Broad  | 186±29           | -3±5             | 0.67±0.07       |
| Inter. | 501±27           | -4±6             | 0.80±0.04       |
| Broad  | 1397±76          | -493±89          | 0.30±0.08       |
| [Ar IV] | A6731            |                  |                 |
| Narrow | 186±29           | -3±5             | 0.66±0.07       |
| Inter. | 501±27           | -4±6             | 0.80±0.03       |
| Broad  | 1397±76          | -493±89          | 0.77±0.08       |

Table 3. Results of the spectral decomposition of the main lines in the spectrum of MRK 477. Three kinematic components are isolated in all cases, including a broad blueshifted component emitted by the ionized outflow. No values are quoted for H$\alpha$ and [NII] because successful fits could only be obtained with full constraints from the [OIII] lines (see Sect. 2.1). The flux of each component relative to H$\beta$ is given in the last column. The exception is H$\gamma$, for which the actual fluxes are quoted.

Figure 6. Spatial profiles (normalized fluxes) of the NIR continuum and Pa$\alpha$ along PA 43° N to E, compared with the seeing disk (star). Both the continuum and Pa$\alpha$ are spatially extended.

by collisional de-excitation. Other line pairs that can overcome this limitation are [Cl III]$\lambda\lambda$5517/5537 ($n_{\text{crit}}=8.5×10^3$ and 2.9×10$^4$ cm$^{-3}$), sensitive at $n$ $\sim$0.4 cm$^{-3}$ and [Ar IV]$\lambda\lambda$4711/4740 ($n_{\text{crit}}=1.7×10^4$ and 1.6×10$^5$ cm$^{-3}$) at $n$ $\sim$10$^3$–10$^5$ cm$^{-3}$.

For MRK 477, [SII]$\lambda\lambda$6716/6731=0.70±0.06, [Cl III]$\lambda\lambda$5517/5537=0.74±0.22 and [Ar IV]$\lambda\lambda$4711/4740 =0.67±0.09, implying densities $n=1945±670$ cm$^{-3}$ (from [SII]), 7250±13300 (from [Cl III]) and $n=14,700^{+6150}_{-5100}$ (from [Ar IV]). So, the [SII] doublet implies the existence of gas with $n$ $\sim$2000 cm$^{-3}$, the [Cl III] doublet, in spite of the larger uncertainties suggests higher densities and the [Ar IV] doublet confirms the existence of gas with $n$ $>$10$^4$ cm$^{-3}$ in the NLR of MRK 477.

3.3 Spatial extension of the ionized gas

The only available information about the spatial distribution of the ionized gas in MRK 477 is provided by the [OIII] image presented by [Heckman et al. (1997)]. It shows a bright knot or ridge of emission at $\sim$0.4 arcsec to the northeast of the central source and aligned with the radio axis. This knot is not resolved from the nucleus in our NIR spectrum, for which the slit was roughly aligned along the same axis. We find, on the other hand, that Pa$\alpha$ is extended at both sides of the central source. We show in Fig. 5 the spatial profiles of (1) a star observed during the May run (seeing size FWHM=0.65±0.05), (2) the MRK 477 continuum and (3) the Pa$\alpha$ flux, with the underlying continuum subtracted. Although more compact than the continuum, Pa$\alpha$ is extended, as demonstrated by the clear excess above the seeing wings, up to a maximum radial distance of $\sim$2 arcsec or $\sim$1.5 kpc to the NE.

3.4 The ionized outflow

[Villar Martin et al. (2014)] performed a kinematic and ionization characterization of the nuclear ionized outflow in MRK 477. Its signature is a broad blueshifted kinematic component in the [OIII]$\lambda\lambda$4959,5007 lines, with
Figure 7. Left: data (black), fits (cyan) and residuals (dashed-red) for a diversity of emission lines. Right: individual kinematic components isolated in each line. Different line styles are used for different kinematic components. The same red colour is used for components with the same redshift: long-dashed red (narrow component), dotted-red (intermediate component), dot-dashed blue (broad component; i.e. the outflow emission). From top to bottom: \([\text{SII}]\lambda\lambda 4068,4076 \text{ and } \text{H}\delta; \text{H}\gamma \text{ and } [\text{OIII}]\lambda\lambda 4363; [\text{NII}]\lambda\lambda 6548,6583 \text{ and } \text{H}\alpha; [\text{SII}]\lambda\lambda 6716,6731.
FWHM~1850 km s\(^{-1}\) and \(V_S \sim\) 225 km s\(^{-1}\). Based on the high turbulence of this gaseous component, the line ratios consistent with AGN (rather than stellar) excitation processes and the relatively high contribution of the outflowing gas to the total line fluxes, the authors proposed that it has been triggered by the 1.2 arcsec scale radio source. This is supported by the correlation between the radio and [OIII] morphologies (Heckman et al. 1997), which demonstrates that the radio source is interacting with the NLR.

3.4.1 Isolating the outflow emission in a diversity of emission lines

By means of the kinematic decomposition of the spectral profiles, we have isolated the emission from the outflowing gas in numerous emission lines (Sect. 2.1). Our goal is to characterize its physical properties and to constrain more accurately its spatial location.

We show in Table 3 the results of the fits for several optical emission lines (see also Fig. 7). FWHM and \(V_S\) correspond to those fits where no prior constraints from [OIII] were applied (method II, see Sect 2.3). When both methods could be applied, the flux values and errors account for the dispersion allowed by them.

Generally, we find rather coherent results for all strong lines for which multiple component fitting procedures could be applied. By “coherent” it is meant that all lines consist of three kinematic components (Table 3), two of them have similar \(z\) and are relatively narrow (FWHM~[95,210] and [470,560] km s\(^{-1}\) respectively). A third broad blueshifted component is moreover isolated in all lines, which is emitted by the outflowing gas. It has FWHM~[1400,1840] km s\(^{-1}\) and \(V_S \sim\) [490,190] km s\(^{-1}\). All the three kinematic components have line ratios consistent with type 2 AGN, as already pointed out by Villar Martin et al. (2014).

Other lines show clear evidence of a broad underlying component, although the triple Gaussian fit is not possible due to the low signal-to-noise and/or the complex blend with neighbour lines. We have calculated the ratio \(\epsilon = \frac{F_{\text{broad}}}{F_{\text{narrow}}}\) between the flux of the broad (outflowing) component and the rest of the line flux (which for simplicity we will name \(F_{\text{narrow}}\), although it contains the narrow and intermediate components) for as many lines as possible. This gives a measurement of the relative contribution between the most turbulent outflowing gas and the more quiescent ambient gas.

The ratio \(\epsilon\) is plotted against \(\log(n_{\text{crit}})\), FWHM, IP\(_{\text{low}}\) and IP\(_{\text{high}}\) in Fig. 8. A significant correlation is found with the critical density \((r_s=0.73, p=0.003;\text{ panel A})\). No significant trend is found with the ionization potentials \((r_s=0.40\text{ and } p=0.15\text{ for }\epsilon \text{ versus }\text{IP}_{\text{low}}\text{ and }r_s=0.35\text{ and }p=0.23\text{ for }\epsilon \text{ versus }\text{IP}_{\text{high}}\)).

An interesting case is the high ionization line [Fe VII]\(\lambda 6087\), for which a very broad component is isolated with FWHM=2460±340 km s\(^{-1}\) (Fig. 9) and \(V_S=\) 150±60 km s\(^{-1}\). Thus, the line which shows simultaneously very high critical density and ionization potential, also shows the most extreme kinematics and the largest \(\epsilon = 0.96\pm0.10\text{ of all optical lines}.\) At the other end, the lowest \(n_{\text{crit}}\) (also low ionization) lines [Ni]\(\lambda 5200\) and [Si]\(\lambda \lambda 6716,6731\), are the narrowest (FWHM~300 km s\(^{-1}\)) and have the smallest \(\epsilon \sim 0.1-0.2\) (Fig. 8).

The correlation between \(\epsilon\) and the FWHM suggests that the increasing broadening of the lines is due to the increasing outflow influence. The correlation with \(n_{\text{crit}}\) shows that the outflow emission is relatively stronger in higher density gas. Ultimately, these results suggest that the FWHM versus \(n_{\text{crit}}\) correlation is produced by the outflow in MRK 477.

[FeII]\(\lambda 1.644\) is the only forbidden NIR line for which the spectral decomposition could be applied. It consists of a narrow, spectrally unresolved component with FWHM\(\leq\)340 km s\(^{-1}\) and a very broad and prominent underlying component with FWHM=4770±530 km s\(^{-1}\) (Fig. 10), shifted by 315±231 km s\(^{-1}\) relative to the narrow core. It is the only line for which the broad component is not blueshifted. For comparison, \(P_{\text{ao}}\) consists of two components with FWHM\(\leq\)260 km s\(^{-1}\) and 2240±230 km s\(^{-1}\) respectively.

\[ \epsilon = \frac{F_{\text{broad}}}{F_{\text{narrow}}} \]
with the broad one blueshifted by $\pm 570 \pm 119$ km s$^{-1}$. As in Fig. 5 [FeII]λ1.64μm is a clear outlier in all $c$ diagrams, with $c=1.3 \pm 0.2$, the highest of all lines. The line, therefore, has a dominant contribution of emission from the outflowing gas. The different behavior of this line will be discussed later (see below).

### 3.4.2 Reddening and electron density

(i) Reddening correction. Reddening correction ($c$ and E(B-V)) has been estimated using the Balmer ratios $\frac{H\alpha}{H\beta}$ and $\frac{H\delta}{H\gamma}$, for which we assume case B values 2.8, 0.47 and 0.26 respectively, appropriate for gas densities $n \sim 10^2-10^6$ cm$^{-3}$ and electron temperatures $T_e \sim 10,000-20,000$ K (Osterbrock 1989).

We show in Table 3 the E(B-V) and $c$ values derived for the three kinematic components and the total line fluxes using the expressions:

$$E(B - V) = 1.99 \times \log \left( \frac{(H\alpha/\beta)_{\text{obs}}}{2.86} \right)$$  \hspace{1cm} \text{[eq.1]}

and

$$\left[ \frac{F}{H\beta} \right]_{\text{int}} = \left[ \frac{F}{H\beta} \right]_{\text{obs}} \times 10^c \left[ f(\lambda) - f(H\beta) \right]$$  \hspace{1cm} \text{[eq.2]}

where “int” and “obs” denote the intrinsic and observed line ratios and $f(\lambda) - f(H\beta)$ is given by the standard interstellar extinction curve (Osterbrock 1989). The final values and errors take into account that negative $c$ values are not allowed.$^4$ Once $c$ is determined, other line ratios are corrected for reddening using the equation (2).

In spite of the complexity of the line profiles, the reddening values derived from the three ratios are in reasonable good agreement. From Table 3 we conclude that the narrowest component shows little or no reddening while the intermediate component shows the highest reddening. For the broad component, the results are less clear, since the Balmer decrement $\frac{H\alpha}{H\beta}$ suggests higher reddening (E(B-V)$=0.32 \pm 0.06$) than the $H\delta$ and $H\gamma$ ratios, which imply little or no reddening. We cannot discard problems with the $H\alpha$ fit, which is severely blended with the [NiII] doublet. However, it might be a real effect. As we will see next, the broad component is expected to have high densities $n \gtrsim 8000$ cm$^{-3}$, maybe up to $\gtrsim 10^5$ cm$^{-3}$, given the detection of very high critical density strong lines. Under these circumstances, the Balmer decrement can be enhanced due to collisional excitation of $H\alpha$, $n \gtrsim 5 \times 10^5$ cm$^{-3}$ will produce $\frac{H\alpha}{H\beta} > 4$ (e.g. Binette et al. 1993). Thus, the inconsistency between the reddening values inferred for the broad component might actually indicate the existence of high densities in the outflowing gas.

We measure $P\alpha/Br\gamma=12.6\pm1.4$ from the NLR spectrum. Taking errors into account, this implies no reddening or, at most, or E(B-V)$<0.32$. This is consistent with the range of values allowed by the optical decrements.

$^4$ This is the reason why in Table 3 the same line ratio with different errors (e.g. $H\alpha/\beta=0.23 \pm 0.04$ and $0.23 \pm 0.06$) can be associated with slightly different $c$ and E(B-V) values.
Figure 11. Constraints on the electron density $n$ for the three kinematic components and for the integrated lines (adapted from Fig. 2 and 3 in Keenan et al. 1996)). A trend is found such that the broader the lines, the higher the density. Thus, the outflowing gas has the highest density.

Table 4. Extinction correction ($c$ and E(B-V)) determined from the Balmer ratios (columns 2, 5 and 8) for the three kinematic components and the integrated lines.

| Comp. | $r_{1obs}$ | $r_{1int}$ | $r_{2obs}$ | $r_{2int}$ | $r_{3obs}$ | $r_{3int}$ | $n$ (cm$^{-3}$) |
|-------|------------|------------|------------|------------|------------|------------|----------------|
| Narrow | 1.03±0.03  | 0.05±0.01  | 0.07±0.02  | 0.007±0.005 | 0.010±0.007 | ∼400-630   |
| Intermediate | 0.73±0.05 | 0.17±0.02 | 0.37±0.09 | 0.08±0.01 | 0.17±0.04 | ∼2000-4000 |
| Broad | 0.41±0.12 | 0.24±0.05 | 0.34±0.14 | 0.08±0.07 | 0.25±0.11 | ≥8000      |
| Total | 0.76±0.06 | 0.13±0.01 | 0.22±0.03 | 0.05±0.01 | 0.08±0.02 | ∼1600-3200 |

Table 5. Density sensitive line ratios observed ($obs$) and corrected ($int$) for reddening. $r_1 = \frac{[SII]_6716}{[SII]_6731}$, $r_2 = \frac{[SII]_4068}{[SII]_6716+[SII]_6731}$, $r_3 = \frac{[SII]_4076}{[SII]_6716+[SII]_6731}$ (Keenan et al. 1996). Unlike $r_1$, these ratios have a strong dependence on the electron temperature $T_e$ and reddening. They are therefore less efficient at constraining $n$, but they provide a useful test. The dependence of both ratios with $n$ and $T_e$ can be seen in Fig. 11.

(ii) Electron density $n$. We have constrained $n$ with the ratio $r_1 = \frac{[SII]_6716}{[SII]_6731}$ (Osterbrock 1989). The results are shown in Table 4. The apparently non-perturbed ambient gas (the narrow component) has $n \sim 400-630$ cm$^{-3}$. The intermediate component, which shows intermediate kinematic and physical properties, has $n \sim 2000-4000$ cm$^{-3}$. Finally, the most extreme kinematic component, which is associated with the outflowing gas, has the highest density $n \geq 8000$ cm$^{-3}$.

We have further checked these results using $r_2 = \frac{[SII]_4068}{[SII]_6716+6731}$ and $r_3 = \frac{[SII]_4076}{[SII]_6716+6731}$ (Keenan et al. 1996). Unlike $r_1$, these ratios have a strong dependence on the electron temperature $T_e$ and reddening. They are therefore less efficient at constraining $n$, but they provide a useful test. The dependence of both ratios with $n$ and $T_e$ can be seen in Fig. 11.

To correct for reddening (eq. [2]), for each component we adopt $c$ as the average of the maximum and minimum values obtained from the three Balmer ratios (Table 4). The uncertainties are calculated using half the difference between
Figure 12. Several narrow Fe$^+$ emission lines are detected in the spectrum of MRK 477. [CaII]λ7291 is also tentatively detected (third panel).

Figure 13. Emission lines are detected from other refractory elements apart from Ca and Fe (Fig. 9), such as possibly Ni (top) and Mg (top and bottom).

Figure 14. Spectral fit, residuals and kinematic components of [OIII]λλ6300,6364. [SII]λ6312 (black small Gaussian) is marginally detected as a small excess on the red side of the [OIII]λ6300. The detection of [FeIII]λ6375 cannot be confirmed. [OII]λ6364 is successfully fitted without the contribution of such a line. Color and line style code as in Fig. 5.
these two values. The results are shown in Table 3 and Fig. 11. In this figure we show the n sensitive diagnostic diagrams log(r1) versus log(r2) and log(r1) versus log(r3) (Keenan et al. 1996). The coloured squares mark the areas covered by the allowed range of extinction corrected line ratios for the different kinematic components and the integrated line fluxes, taking into account all the uncertainties. The figure is consistent with the results from r1. They support a trend for increasing density from the narrow to the broad component.

In spite of the uncertainties inherent to fitting the multiple kinematic components in all the lines involved in the determination of n and reddening, a coherent picture can be drawn: the ionized gas within a radius of 1.5 arcsec or ~1.1 kpc (set by the size of the SDSS fibre) shows a gradient in physical and kinematic properties, which is apparent in the three kinematic components. The apparently non-perturbed ambient gas (the narrow component) has \( n \sim 400-630 \text{ cm}^{-3} \). The intermediate component, which shows intermediate kinematic and physical properties, has \( n \sim 2000-4000 \text{ cm}^{-3} \). Finally, the broadest component, which is associated with the outflowing gas has the highest density \( \geq 8000 \text{ cm}^{-3} \). As mentioned above, the large \( \frac{H_\beta}{H_-} \) decrement might suggest densities as high as \( n > 5 \times 10^5 \text{ cm}^{-3} \) for the outflowing gas.

3.5 Narrow optical Fe\(^+\) emission

Broad Fe\(^+\) multiplet emission are prominent features in the optical spectra of most type 1 AGNs. Dong et al. (2010) have demonstrated statistically that narrow optical Fe\(^+\) lines, either permitted or forbidden, are prevalent in type 1 AGNs, but are completely absent in type 2 AGNs across a wide luminosity range, from Seyfert 2 galaxies to QSO2.

MRK 477 is an exception. Heckman et al. (1997) detected [FeII]λ6867 blended with some neighbour lines. We confirm the detection of more than 10 Fe\(^+\) emission lines (see Table 1 and Fig. 12), besides several other features that might be blended or misidentified. The features for which the width could measured show FWHM \( \sim 400-650 \text{ km s}^{-1} \), suggesting similar kinematics as the NLR (Fig. 5 top panels). Other emission lines associated with highly refractory elements are also detected (Mg, Ni and, tentatively, Ca; Figs. 12 and 13).

3.6 Coronal lines

Coronal lines are collisionally excited forbidden transitions emitted within low-lying levels of highly ionized species (IP\(_{\text{low}} > 100 \text{ eV}\); Rodríguez Ardila et al. 2006). According to that exact definition, we cannot confirm the detection of any coronal feature in the optical spectrum of MRK 477, since the highest ionization lines we identify unambiguously are those produced by Fe\(^{+6}\) (IP\(_{\text{low}} = 99 \text{ eV}\)). On the other hand, coronal emission is confirmed in the NIR spectrum with the detection of [SiVI]λ1.963 (IP\(_{\text{low}} = 167 \text{ eV}\)) and [SiX]λ1.430 (IP\(_{\text{low}} = 351 \text{ eV}\)) (Fig. 4, Table 2).

Although [FeX]λ6375 (IP\(_{\text{low}} = 235 \text{ eV}\)) was reported as detected by De Robertis (1987) and Veilleux (1988), we cannot confirm this. Both groups used the same spectra in their analysis, one obtained in 1980 and another in 1985. The 1985 spectrum shows a strong emission feature at the right \( \lambda \) (see their Fig. 6, left), but this was discarded by Veilleux (1988) as an artifact. Although the 1985 spectrum shows a small excess near the [FeX] wavelength which the authors interpret as the detection of this line, our analysis shows that this is consistent with being due to the complex kinematic sub-structure of the [OI]λ6374 line profile (Fig. 13).

A broad faint and noisy feature is detected with central \( \lambda = 7888.8 \text{ Å} \). Several lines are possibly contribut-
2 AGN (Penston et al. 1984; Rose et al. 2013) cannot be con-
fi rm ed either.

The highest optical ionization lines unambiguously iden-
tifi ed are [NeV]λ3346.3426 (IP_{low} =97 eV, out of the SDSS
spectral range; reported by De Robertis 1987) and the [Fe-
VII] lines (IP_{low} =99 eV) at λ 5159, 6087 Å (also reported
by De Robertis 1987), and lines at 3759, 4893, 5721 Å. Also
possibly [FeVII] at 5276 Å, [ArX] at 5533 Å, although other
identifi cations cannot be discarded (Table 1).

With somewhat lower ionization level, [CaV] at 5309 Å
(IP_{low} =67 eV) and several [FeVI] (IP_{low} =75 eV) lines at
5146, 5176, 5335, 5485, 5631, 5677 Å are also detected and
possibly [FeV]λ5726 (IP_{low} =55 eV) and [FeVII] at 5426 Å.

[FeVII]λ6086 is fainter relative to low ionization lines
(e.g. [OI]λ6300) than usually found in active galaxies
with strong coronal emission. [FeVII]λ6086 =0.15±0.01 for
MRK 477. For comparison, the Seyfert 1 and 2 galax-
ies studied by Rodriguez Ardila et al. (2006) with detected
[FeX] and [FeXI] lines show in general (4 out of 5 objects)
[FeVII]λ6086 in the range =0.6-5.7.

3.7 The WR bumps

Heckman et al. (1997) detected a broad emission complex
around He IIλ4686, which is clearly appreciated in the SDSS
spectrum. They fi tted this so called “blue bump” satisfac-
torily as a blend of the He II line together with other lines
which are identifi ed in Fig. 13 (top). This unresolved bump is a blend of lines emitted mainly by late WN and early WC
WR stars, although some contribution of early WN stars
might be present (Schaerer & Vacca 1998). Heckman et al.
(1997) propose that it may be produced by an ensemble
of about 30,000 WR stars (WN subtype), in which case
MRK 477 would be a luminous (but not extraordinarily so)
member of the class of WR galaxies.

Another feature often identifi ed in WR galaxies due
to WR stars is the so called “red bump” due to broad
CIVλ5808 emission, emitted mainly by WCE stars. This is
usually much weaker than the “blue bump” and was not
detected by Heckman et al. (1997).

We show in Fig. 13 (middle panel) the MRK 477 spectrum
near the “red bump” and the optical spectrum of the WR
galaxy SBS 1222+614 (Guseva, Izotov & Thuan 2000)
for comparison (bottom panel). The appearance of the “red
bump” in this and other WR galaxies is very similar to that
in MRK 477. We thus believe that the “red bump” is
detected in the SDSS spectrum of this QSO2. Its very large
width (FWHM =80 Å or =1400 km s^{-1}) rules out as its
origin the broad wings due to the ionized outflow identifi ed
in many other emission lines.

4 DISCUSSION

We have analysed the optical and NIR spectra of MRK 477,
the nearest obscured quasar. WR features fi rst identifi ed by
Heckman et al. (1997) and confi rmed here by the new
 detection of the “red bump” at =5800 Å (Sect. 3.7) show
that it has undergone very recent star formation.

The optical+NIR spectrum of MRK 477 is very rich,
with =100 detected emission lines (=90 in the optical). In
spite of the lack of spatial information of the SDSS spectrum,
the spectral decomposition of numerous lines has allowed us
to characterize, at least partially, the spatial structure and
the gradients in the physical and kinematic properties of the
gas.

4.1 The origin of the FWHM versus n_{crit} correlation

As in many other type 1 and type 2 AGN, a signifi cant
 correlation has been found between the FWHM of the lines
and the critical density n_{crit} (in log). Based on the analysis
of eight type 1 AGN spectra, Stern, Laor & Baskin (2014; S14 hereafter) showed that this relation is consistent with the
velocity field within the black hole gravitational sphere
of infl uence (radius R_{g}), assuming the n ∝ R^{-2} relation
implied by the equilibrium between the NLR clouds and the
radiation pressure and that the emission of each forbidden
d line is dominated by gas with n ∝ n_{crit}. This explanation
implies that beyond some threshold n_{crit}, n_{crit}, which
depends on the luminosity in Eddington units m, the line
emission will be dominated by gas within R_{g}, and therefore
is expected to show larger velocities than gas which kine-
matics is dominated by the host galaxy. For MRK 477, the
stellar velocity dispersion σ_{s} =117 km s^{-1} (Zhang, Bian &
Wang 2008), L_{bol} and the values of M_{BH} quoted in Sect. 1
imply R_{g} ∼ 10 and 40 for log(M_{BH})=7.19 and 8.84 respec-
tively (eq. 26 in S14). This implies a threshold n_{crit}=10^{0.6}
cm^{-3} (eq. 6 in S14) for log(M_{BH})=7.19. This value is much
larger than the n_{crit} ∼10^{-5.4} cm^{-3} where the FWHM
starts to increase in MRK 477 (top-left panel in Fig. 5),
which makes the gravitational interpretation unlikely. For
the success of this prediction supports the gravitational
interpretation for the FWHM versus n_{crit} correlation,
provided MRK 477 harbors such a massive black hole. On
the other hand, the kinematic substructure of the lines raises
doubts about whether the emission is truly emitted mostly
gas by gas at n ∝ n_{crit}. As an example, the [OIII] line fl ux is
dominated by gas with n ≤7000 cm^{-3} (see Sect. 3.4).

Alternatively, we propose that the outflow produces this
correlation in MRK 477. Thiss supported by the correla-
tions between ε = F_{FWHM}/F_{bol} and n_{crit} (Sect. 3.3.1),
which imply that the outflow is relatively stronger and is respon-
sible for the increasing line broadening at increasing densities.
This correlation does not differ in any statistical sense from
the usual FWHM versus n_{crit} one. The difference lies in
the physical interpretation we propose.

It is possible that the effects of ionized outflows explain
the FWHM versus n_{crit} correlation in other AGN.

Three kinematic components have been isolated in
the main optical emission lines. The narrowest and inter-
mediate components, have similar z (V_{S} ∼0 km s^{-1})
and are relatively narrow (FWHM∼95-210) and [470-560]
kms respectively). A third broad blueshifted component is
moreover isolated in all lines with FWHM in the range
∼[1400-1840] km s^{-1} and V_{S} ∼[−490] km s^{-1}. The
narrow component is likely to trace the NLR ambient, non
perturbed gas, while the broad component is emitted by the
most turbulent, outflowing gas. The intermediate compo-
nent traces gas of intermediate properties. All three com-
ponents have line ratios consistent with type 2 active galax-
ies, as already pointed out by Villar Martin et al. (2014).
implying that they are spatially located within the quasar ionization cones.

The difference in kinematics is associated with a difference in physical properties. The broader the component, the higher the density. The sequence we find is \( n \sim (400-630) \text{ cm}^{-3} \) for the ambient gas, \( n \sim (2000-4000) \text{ cm}^{-3} \) for the intermediate component and \( n \gtrsim 8000 \text{ cm}^{-3} \) for the outflowing gas (see §3.3.2). Higher \( n \) of the outflowing gas is also suggested by the correlation between \( \epsilon = \frac{L_{\text{bol}}}{n R_{\text{crit}}} \) and \( R_{\text{crit}} \), for different forbidden lines (see above). Density enhancement of the outflowing gas has been found in some radio galaxies and QSO2 (e.g. Holt et al. 2011, Villar Martín et al. 2014).

### 4.2 The spatial location of nuclear ionized outflow

The isolation of the broad component in numerous emission lines demonstrates that the outflow involves gas covering a large range of ionization potentials and critical densities (at least \( P_{\text{high}} \sim 8 \) to 125 eV, \( \log(n_{\text{crit}}) \sim 3.3 \) to 7.5). We try to constrain next the spatial location where it was triggered and how far its effects extend.

Bennert et al. (2006a,b) found that the observed gas density of the NLR gas decreases with increasing distance to the AGN in Seyfert 1 and 2 galaxies (see also S14). A similar behavior is expected in MRK 477. The difference in kinematic and physical properties between the broad, intermediate and narrow components can be naturally explained if they are located at increasing distance from the AGN, with the outflow emission dominating at smaller distances, in the inner part of the NLR or even closer (see also Villar-Martín et al. 2014). The outflow becomes weaker as it propagates outwards and reaches less dense regions, where lines of lower critical densities are preferentially emitted. Because the outflow has lost some power, it drags less and less mass and its emission becomes weaker relative to the ambient gas, which dominates the line fluxes in the most distant, lower density regions. This can also explain the correlation of \( \epsilon \) with \( n_{\text{crit}} \).

If the radiation pressure is responsible for the NLR density gradient (S14), the estimated \( n \) for the three kinematic components will help to constrain the distance from the central engine \( R \) at which each one is preferentially emitted. The expected behaviour of \( n \) with the ionizing luminosity \( L_{\text{ion}} \) and \( R \) is predicted to be (S14):

\[
n = 7 \times 10^4 L_{\text{ion}, 45} R_{50}^{-2}
\]

where \( L_{\text{ion}, 45} \) is the ionizing luminosity in units of \( 10^{45} \text{ erg s}^{-1} \) and \( R_{50} \) is the distance in units of 50 pc.

Typical \( \frac{n}{L_{\text{ion}}} \) ratios for luminous Sy1 and QSO1 with \( L_{\text{bol}} \) in the range \( \sim 10^{45-46} \text{ erg s}^{-1} \) have median value of 3.89 and standard deviation 4.36. Thus, for a ratio of 3.89, then \( L_{\text{ion}, 45} \sim 2.2 \) for MRK 477. Considering the range of \( n \) inferred for each gaseous component, the broad (outflowing), intermediate and narrow kinematic components would be located at \( \lesssim 220 \) (the upper limit is a consequence of the lower limit on \( n \gtrsim 8000 \text{ cm}^{-3} \)), 375±65 and 880±100 pc respectively. This sets an upper limit on the distance at which the outflow has been originated of \( R \lesssim 220 \text{ pc} \). If densities as high as \( \sim 5\times 10^3 \text{ cm}^{-3} \) exist in the outflowing gas (Sect. 3.4.2), then \( R \lesssim 30 \text{ pc} \). For comparison, the radio jet extends at \( \sim 0.6 \text{ arcsec} \) or 435 pc from the central engine. With all uncertainties involved, it is remarkable that these calculations place the intermediate and narrow components near and beyond the edge of the radio jet respectively. This adds further support to the idea that the radio jet has originated the outflow. In this scenario, our results suggest that the outflow in MRK 477 is concentrated in the nuclear region and does not reach distances beyond \( \sim \text{few} \times 100 \text{ pc} \).

Alternatively, the higher density of the outflowing gas might be explained by the compression exerted on the outflowing gas by the radio-jet induced shocks (Villar Martín et al. 1999, Holt et al. 2011). We note that this scenario is qualitatively different from the scenario where the NLR clouds are compressed by radiation pressure, as assumed in the models used above. The higher density would instead be located at or near the radio jet and decrease moving away from it. In this case a correlation would be expected between the morphology of the radio jet and the ionized gas (whose emission is enhanced due to shock excitation and/or density enhancement). This is actually the case in MRK 477 (Heckman et al. 1997). Both the radio and [O II] images show a bright knot or ridge of emission about 0.4 arcsec (\( \sim 290 \text{ pc} \)) to the northeast of the central source. This clearly shows that the radio jet is interacting with the NLR and enhancing the emission at this location. Thus, an alternate scenario is that this detached knot is responsible for the bulk of emission of the outflowing gas. If so, it must emit a wide range of lines, including [Fe II] at 6087. High spatial resolution spatially extended optical spectroscopy would help discriminate between both scenarios.

### 4.3 The origin of the NIR narrow [FeII] 1.644 emission

We have found that this line is much broader than expected for its critical density and ionization potentials (Sect. 3.2). The underlying broad component has FWHM\( \sim 4770 \pm 830 \text{ km s}^{-1} \), larger than any other line and contributes more than half of the total line flux (\( \sim 57\% \)). It also shows the largest \( \epsilon =1.3 \pm 0.2 \) and is the only line for which the broad component is not blueshifted. All these could be naturally explained in terms of reddening being much weaker in the NIR, so that both the approaching and receding parts of the expanding outflow are observed (unlike the optical lines). However, this is an unlikely explanation since Pao shows that the broad component is blueshifted by \( \sim 570 \pm 119 \text{ km s}^{-1} \).

Alternatively, it is possible that [FeII] 1.644 is relatively enhanced by the shocks induced by the outflow, more than other lines and at a less obscured spatial location (hence the non-blueshift). Outflow induced shocks have been often proposed as a relevant [FeII] 1.644 excitation mechanism in active galaxies (e.g. Ramos Almeida et al. 2009, Contini et al. ?). As an example, ? studied the kinematics and excitation mechanism of the NIR emission lines in a sample of Seyfert 1 galaxies, including [FeII] 1.257 and 1.645 \( \mu \text{m} \). They found 3 out of 22 sources in which the [FeII] lines were the broadest, even broader than the coronal [SIX] 1.252 \( \mu \text{m} \). They suggest that in these objects [FeII] must arise from and additional source, partially formed in a region distinct from other low-ionization species, which they suggest to be associated with shock excitation from the radio jet. Bietz et al. (1995) also suggest that the [FeII] 1.644 emission in the Sy2
galaxy NGC1068 is preferentially emitted by gas which is interacting with the nuclear outflow/jet and is possibly located at the interface between the outflow and the dense circumnuclear molecular clouds.

4.4 Coronal lines
Detection of coronal emission is confirmed in the NIR spectrum, but not in the optical (Sect. 3.6). In the optical, the highest ionization lines are those emitted by Fe\(^{+6}\), which on the other hand are fainter relative to the low ionization lines than typically found in AGN with strong coronal emission. Coronal lines are generally detected between just a few parsecs and a few hundred parsecs (e.g. Mazzalay et al. 2010, 2014). They have been proposed to be formed in a region located at an intermediate distance between the classical NLR and the broad-line region (BLR) (Müller Sánchez et al. 2002). Alternatively, the coronal region might reside in the inner wall of the dusty torus (Murayama & Taniguchi 2006). Alternatively, the coronal region might reside in the inner wall of the dusty torus (Murayama & Taniguchi 1998, Rose et al. 2013) or in the low density surface layer of the SDSS fibre (radius \(<1\) kpc from the nucleus) and much more concentrated than lower ionization NLR features (Rodríguez Ardila et al. 2011), it is also possible that they are diluted by the strong continuum contribution within the large aperture of the SDSS fibre (radius \(\sim1\) kpc).

The [SiVI] and [SiX] lines have luminosities 40.0 and 30.8 in log and erg s\(^{-1}\) respectively. Rodríguez Ardila et al. (2011) found that these lines display a narrow range in luminosity in Seyfert 1 and 2, with values for most objects located in the interval log(\(L\))=-39-40. MRK 477 is at the high end of this range. We measure [SiVI]/[SiX]=1.6±0.1, also within the range measured for Seyfert 1 and 2 galaxies by those authors.

4.5 Detection of narrow optical Fe\(^{+}\) emission
We have identified more than 10 narrow optical Fe\(^{+}\) emission lines in the SDSS spectrum of MRK 477. The NLR He\(^{+}\) lines at 1.26 and 1.64 \(\mu\)m are routinely detected in type 2 Seyferts (e.g. Ramos Almeida, Pérez García & Acosta-Pulido 2009). However, to our knowledge MRK 477 is the first type 2 AGN with optical Fe\(^{+}\) line detections.

To explain the absence of narrow optical Fe\(^{+}\) in type 2 AGN, while being prevalent in type 1 objects, Dong et al. (2014) proposed that such emission is confined to a disk-like geometry in the innermost region of the NLR on physical scales of parsecs. This would be smaller than the obscuring torus and within the dust sublimation radius. Iron, which is a refractory element which easily condenses on to dust grains, is in the gaseous phase in the absence of dust (Laor & Draine 1993). In this scenario the narrow optical Fe\(^{+}\) emitting region is visible along our line of sight in type 1 objects, but obscured by the extent of the dusty torus in type 2 counterparts.

It is however difficult to picture a geometry such as this to explain the optical Fe\(^{+}\) emission in MRK 477. Broad permitted hydrogen and helium lines would be expected, unless a BLR did not exist, but this is not the case (Sect. 1).

We explore next whether the optical Fe\(^{+}\) features can be naturally explained by the intrinsic NLR emission. For this, we compare the measured integrated flux relative to H\(\beta\) of all Fe\(^{+}\) lines in the blue (4000-6000 Å) and red (6000-7800 Å) bands with the ratios predicted by photoionization models appropriate for the NLR conditions. We use the radiation-pressure-confined NLR models described in S14. The assumption of these models implies that the line emission is essentially independent of the ionization parameter at the slab surface \(U_0\), as long as \(U_0\geq0.03\) (see Fig. 3 in S14; see also Dopita et al. 2002 and Groves et al. 2004). A continuous distribution of dusty gas as a function of the distance from the nucleus \(R\) is considered. This distribution is characterized by \(\eta\), the power-law index of the dusty gas covering factor as a function of logarithmic unit of \(R\). These types of models are successful in explaining various observations of the NLR (see Dopita et al. 2002 and S14).

We assume solar metallicity, an ionization slope of \(\alpha_{ion}=-1.6\) typical of luminous quasars (Telfer et al. 2002), and \(\eta=0\), i.e. a constant covering factor per log \(R\), as suggested by the strong line ratios and the IR spectral energy distribution (S14). The photoionization models are calculated using CLOUDY (Ferland et al. 2013), assuming hydrostatic equilibrium. Depletion of refractory elements on to dust grains is taken into account, and the Fe\(^{+}\) ion is calculated according to the model described in Verner et al. (1999).

The results for the FeII(4000 – 6000)/H\(\beta\) and FeII(6000 – 7800)/H\(\beta\) are shown in Table 6 considering both dusty and non-dusty models. The uncertainties on the observed ratios account for the errors on the flux measurements and the possible misidentification of some features (Table I). The models can reproduce successfully both the blue and the red bands. Therefore, the narrow optical Fe\(^{+}\) lines in MRK 477 can be naturally explained by the intrinsic NLR emission due to AGN photoionization. The high luminosity and/or closeness of MRK 477 could be the reason why these lines have been detected, unlike other type 2 AGN.

The effect of dust depletion produces ratios approximately twice lower than those derived from dust-free models. Taking into account the uncertainties, the Fe\(^{+}\) band ratios do not discriminate between the two scenarios. Model predictions of lines emitted by other refractory elements such as Mg, Ni, Ca (also detected for MRK 477, see Sect. 3.5) would help to infer whether the NLR contains dust-free gas. Only the [CaII]\(\lambda\)7291 is predicted by CLOUDY. Calcium is much more sensitive to dust depletion than iron. The dust-free models predict [CaII]\(\lambda\)7291/H\(\beta\)=0.08, while the line would be 1000 times fainter (and thus undetectable) in the dusty case (see also Villar Martín et al. 1996). The [Ca II] line is tentatively detected with a ratio of 0.02±0.01 relative to H\(\beta\) (Fig. 12 third panel). If this detection is confirmed, it would imply that at least a fraction of the NLR gas is dust free.
5 CONCLUSIONS

We perform a detailed spectral analysis and characterization of the NLR of the nearest obscured quasar (QSO2) MRK 477 at z=0.037 based on the SDSS optical and NIR H+K spectra obtained with WHT-LIRIS.

(i) We confirm the hybrid nature (AGN+starburst) proposed by Heckman et al. (1997) based on the new detection of the “red bump” at ~5800 Å due to WR stars, which implies that the system has undergone recent star formation.

(ii) The optical spectrum of MRK 477 is rich in emission lines, with ~90 detected features. In spite of the lack of spatial information of the SDSS spectrum, the spectral decomposition of numerous lines has allowed us to characterize, at least partially, the spatial structure and the gradients in the physical and kinematic properties of the gas.

(iii) Gas densities within the range 1945±460 and up to 10^4 cm^-3 are confirmed in the NLR of MRK 477.

(iv) As in many other active galaxies (AGN), a significant correlation is found between the lines FWHM and the critical density log(n_crit). We propose that this correlation is caused by the outflow and its impact on the gas kinematics. This could be the case in other AGNs.

(v) MRK 477 is an example of a radio quiet powerful AGN where negative feedback (the nuclear outflow) can be dominated by the radio structures. The outflow emission has been isolated in many emission lines covering a large range of ionization potentials and critical densities (from [OI]λ6300 to [FeVII]λ6086). The outflowing gas, which is concentrated within R~few×100 pc from the central engine, is >13 times denser (n >8,000 cm^-3) than the ambient non perturbed gas (n ~400-630 cm^-3). Marginal evidence is found for densities as high as n >5×10^5 cm^-3 in the outflowing gas. It is possible that the density enhancement is due to the gas compression produced by jet induced shocks. This is supported by the correlation between the radio and [OIII]λ5007 morphologies found by Heckman et al. (1997).

Alternatively, the density enhancement is not related to the jet. Instead, it might be a reflection of the NLR intrinsic density gradient, consequence of the gas being compressed by radiation pressure. In this scenario, and based on the comparative study between the density and the kinematic properties of the outflowing and the ambient gas, we conclude that the outflow has been generated at ~220 pc (possibly at ~30 pc) from the AGN. We find evidence of how its effects weaken as it propagates outwards, following the NLR density gradient. Beyond the radio jet edge, the gas emission is dominated by ambient less dense, non perturbed gas. This adds further support to the idea that the radio jet has triggered the outflow.

(vi) The [FeII]λ1.644μm line presents a very different behaviour than the rest of the emission lines. It shows the most extreme effects of the outflow, with an underlying broad component of FWHM=4770±830 km s^-1. Its properties suggest that its emission is enhanced by shocks induced by the nuclear outflow/jet and is preferentially emitted at a different, less reddened spatial location, maybe the interface between the outflow and the dense circumnuclear molecular clouds.

(vii) More than 10 narrow optical Fe^+ emission lines have been detected in the SDSS spectrum of MRK 477. To our knowledge, this is the first type 2 AGN with such a detection. We show that these lines can be explained as the natural emission from NLR gas photoionized by the AGN. Emission lines associated with other highly refractory elements (Mg, possibly Ni) are also detected. If the tentative detection of the [Ca II]λ7291 line is confirmed, this would imply that at least part of the NLR gas is dust-free.

(viii) Coronal line emission is confirmed in the NIR, but not in the optical SDSS spectrum. The coronal region might be heavily reddened, partially hidden from our line of sight. Alternatively its optical emission might be diluted due to the large SDSS fibre aperture. The coronal region also participates in the outflow.

(ix) Paα is spatially extended along the radio and [OIII] emission axes, up to a maximum radial extension of ~1.5 kpc from the AGN.

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