First black hole mass estimation for the quadruple lensed system WGD2038-4008

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ABSTRACT

Context. The quadruple lensed system WGD2038-4008 ($z_s = 0.777 \pm 0.001$) has recently been discovered with the help of new techniques and observations. Black hole masses have been estimated for lensed quasars, but they have mostly been calculated for one broad emission line of one image. However, the images could be affected by microlensing, which changes the results.

Aims. We present black hole mass ($M_{BH}$) estimations for images A and B of WGD2038-4008 using the three most prominent broad emission lines (Hα, Hβ, and MgII) obtained in one single-epoch spectra. This is the first time the mass has been estimated in a lensed quasar in two images, allowing us to disentangle the effects of microlensing. The high S/N of our spectra allows us to get reliable results that can be compared with the existing data in the literature.

Methods. We used the X-shooter instrument mounted on the Very Large Telescope at Paranal Observatory to observe this system, taking advantage of its wide spectral range (UVB, VIS, and NIR). The sky emission correction was performed using principal component analysis as the nodding was small compared to the image separation. We compared the lines profiles to identify the microlensing in the broad-line region and corrected each spectrum by the image magnification. Using the flux ratio of the continuum to the core of the emission lines, we analyzed whether microlensing was present in the continuum source.

Results. We obtained $M_{BH}$ using the single-epoch method with the Hα and Hβ emission lines from the monochromatic luminosity and the velocity width. The luminosity at 3000 Å was obtained using the spectral energy distribution of image A, while the luminosity at 5100 Å was estimated directly from the spectra. The average $M_{BH}$ between the images obtained was $\log_{10}(M_{BH}/M_\odot) = 8.27 \pm 1.05, 8.25 \pm 0.32$, and $8.59 \pm 0.35$ for MgII, Hβ, and Hα, respectively. We find Eddington ratios similar to those measured in the literature for unlensed low-luminosity quasars. Microlensing of $-0.16 \pm 0.06$ mag in the continuum was found, but the induced error in the $M_{BH}$ is minor compared to that associated with the macromodel magnification. We also obtained the accretion disk size using the $M_{BH}$ for the three emission lines, obtaining an average value of $\log_{10}(r_d/cm) = 15.3 \pm 0.63$, which is in agreement with theoretical estimates.

Key words. gravitational lensing: strong – gravitational lensing: micro – quasars: individual: WGD2038-4008 – black hole physics – quasars: supermassive black holes

1. Introduction

The number of lensed quasars discovered is consistently growing thanks to the help of new identification techniques and observations (Agnello et al. 2018; Krone-Martins et al. 2019; Lemon et al. 2020). Here, we study one of these recently identified lenses, WGD2038-4008. This system is a quadruple lensed quasar discovered in 2017 using a combination of Wide-field Infrared Survey Explorer (WISE, Wright et al. 2010) and Gaia (Gaia Collaboration 2016) over the Dark Energy Survey (DES, Dark Energy Survey Collaboration 2016) footprint with a source and deflector redshift of $z_s = 0.777 \pm 0.001$ and $z_D = 0.230 \pm 0.002$ respectively (Agnello et al. 2018). The deflector is a red galaxy with a compact bulge and a bright halo while the source has an extended quasar host galaxy (Agnello et al. 2018). It was observed using the Hubble Space Telescope (HST) obtaining a lens model for this system (Shajib et al. 2019) using LENSTRONOMY (Birrer & Amara 2018). Spatially resolved narrow-line fluxes ([OII] in Nierenberg et al. 2020) are also available. Buckley-Geer et al. (2020) studied the lensing galaxy to measure its velocity dispersion and to identify the line-of-sight galaxies that need to be included in the lens model. Even though gravitational lensed quasars are a powerful tool for studying the inner structure of active galactic nuclei (AGNs; Pooley et al. 2007; Anguita et al. 2008; Pointdexier et al. 2008; Dai et al. 2010; Morgan et al. 2010; Treu 2010; Jiménez-Vicente et al. 2014; Motta et al. 2017), no such study has been conducted to date for WGD2038-4008. One of the difficulties of working with lensed quasars is that microlensing can affect different regions of the broad emission lines (BELs) in the spectra of one or more images of the system (Mediavilla et al. 2011; Motta et al. 2012; Guerras et al. 2013; Fian et al. 2018; Rojas et al. 2020). Microlensing
can affect the observed flux of the accretion disk and the BELs, as well as the shape of the BELs, ultimately adding uncertainty to the single-epoch black hole mass ($M_{BH}$) estimation.

Precise measurement of the $M_{BH}$ is key to understanding the coevolution between the supermassive black hole (SMBH) growth and the host galaxy (see Ferrarese & Ford 2005; Kormendy & Ho 2013). In particular, physical parameters of the SMBH seem to correlate well with the luminosity (Marconi & Hunt 2003) and velocity dispersion (Ferrarese & Merritt 2000; Tremaine et al. 2002) of the host galaxy.

The single-epoch (SE) method is one of the most widely used technique to measure $M_{BH}$ in AGNs: it relates the continuum luminosity of the quasar at a particular wavelength with the size of the broad-line region (BLR; see Vestergaard 2004; Shen & Liu 2012; Mejía-Restrepo et al. 2016). Typically, the SE masses for low-redshift quasars ($z < 0.7$) are estimated in the optical using Hα and Hβ BELs and the continuum luminosity at 5100 Å.

However, the Balmer lines are shifted into the infrared at higher redshifts, thus most of the estimations have been measured in the UV wavelength using MgII and CIV BELs. Over the last decade, the SE method has been used to obtain $M_{BH}$ in lensed AGNs (Peng et al. 2006; Greene et al. 2010; Assef et al. 2011; Sluse et al. 2012; Mediavilla et al. 2018), but most of them from the MgII and CIV BELs, and none of them using different emission lines observed simultaneously.

In this paper we present high signal-to-noise ratio (S/N) SE spectra for the quadruple lensed system WGD2038-4008 to obtain the $M_{BH}$ for three emission lines (Hα, Hβ, and MgII) for two of the images. We also study microlensing in the emission lines and in the continuum, and finally we obtain the velocity dispersion of the lensing galaxy.

The paper is organized as follows. In Sect. 2 we present the data along with the reduction and the extraction of the spectra for each component. Section 3 shows the description of the method used for the estimation of the $M_{BH}$, microlensing analysis, and velocity dispersion of the lensing galaxy. We present our results in Sect. 4 comparing with previous studies of different lensed quasars and finally our conclusions are presented in Sect. 5.

We assume a Lambda cold dark matter (ΛCDM) cosmology with: $\Omega_M = 0.7$, $\Omega_{\Lambda} = 0.3$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. Observation and data reduction

2.1. Observational strategy

We obtained spectra for WGD2038-4008 during July 2019 as part of ESO proposal ID 103.B-0566(A) (PI: A. Melo) using the X-shooter instrument mounted at the 8.2 m UT2 at the Very Large Telescope (VLT), Paranal Observatory, Chile (Vernet et al. 2011). X-shooter is a medium-resolution spectrograph that observes in a wide spectral range, from ultraviolet (UVB; 3000–5600 Å), through visible (VIS; 5500–10200 Å), and up to the near-infrared (NIR; 10200–24800 Å). We used three observing blocks (OBs) taken on two different nights with an average seeing of 1.12′′. The UVB slit was 1.0′′×11′′ (spectral resolution $R = 5400$), while the VIS and NIR slits were 1.2′′×11′′ ($R = 6500$ and 4300, respectively) with a readout mode (UVB and VIS) of 100k/1pt/kg and a nodding of 3′′ per individual frame. Each UVB/VIS (NIR) OB consists of 2 (4) exposure frames. The atmospheric dispersion corrector (ADC) is used to avoid chromatic differential atmospheric refraction. Table 1 summarizes the main observational characteristics of WGD2038-4008.

The slit position was chosen to cover the two brightest source images, centered on image B of the gravitational lensed quasar with a position angle on the sky of 126.8514° to include image A (see Fig. 1).

![Fig. 1. Scheme of the slit position centered on image B (RA 307.5115875, DEC -40.13736167, epoch J2000) of WGD2038-4008. The FITS image is from the Dark Energy Survey in filter r (Gravitational Lensed Quasar Database https://research.ast.cam.ac.uk/lensedquasars/).](image-url)

2.2. Data processing

We used the ESO pipeline EsoReflex (Freudling et al. 2013) workflow with the X-shooter pipeline version 3.5.0 to reduce each OB without using nodding to subtract the sky emission. This method was employed instead of the standard method because the 3′′ nodding is comparable to the image separation (∼2.87′′), which causes a self-subtraction flux from the lensed quasar spectra. The next steps in the reduction and extraction were slightly different for the three arms of the instrument. Once the frames were corrected by cosmetics (flat field, dark current, wavelength calibration, among others), we proceeded to subtract the sky emission in the NIR arm. We designed a sky emission correction for each individual frame based on principal component analysis (PCA, Deeming 1964; Bujarrabal et al. 1981; Francis & Wills 1999), a method normally used in multi-dimensional analysis. PCA uses a basis of eigenvectors that are constructed to describe the data (e.g., by maximizing the variance of the projected data). This method is usually applied to reduce the number of parameters describing a data set by computing the principal components to change the representation of the data. The number of components used in the reconstruction was chosen to minimize the standard deviation of the residuals between the spectrum and all sky models (using a different number of components). The procedure used to obtain the best representation of the underlying sky emission in each frame consists of the following steps. First, we masked the outliers (such as bad pixels) using σ-clipping ($\sigma = 5$ with three iterations), replacing them with an estimated value obtained from a bicubic interpolation using the surrounding pixels. Then, we calculated the median for each wavelength bin to obtain a rough approximation of the sky emission as a function of the wavelength. We note that this value is only used to identify the targeted spectra (quasar lensed images A and B, as well as the lens galaxy). We subtracted this rough sky median from each frame and collapsed the remaining 2D spectra along the wavelength (see Fig. 2 right and left, respectively) to select an uncontaminated spatial region for the sky emission. A threshold equal to 3 pixels, above and below the dispersion of the median, above the background (see Fig. 2, left) is applied to choose the region to be employed as the PCA-basis (normalized to the unit). The PCA eigenvector basis is obtained by constructing a model of the sky emission in the selected spatial region. This 2D sky model is then subtracted from the frame.
Flux calibration is done by using the response curve from the end-products of the X-shooter pipeline. This response is obtained from a standard star observed the same night as the target, in our case GD153, EG 274 and Feige 110 for OB 1, 2, and 3, respectively.

After the sky modeling and subtraction, we employed molecfit (Smette et al. 2015; Kausch et al. 2015) in each frame to correct by telluric absorptions. For each frame, the target spectra were median-combined into a single spectrum in order to increase the signal and decrease the noise. The spatial region occupied by the targets was previously calculated during the PCA sky emission estimation, and corresponds to the source emission region in Fig. 2. The molecfit best fit was applied to each frame row by row. Once the frames were corrected by sky emission and telluric absorption, they were median combined each frame row by row. Once the frames were corrected by sky subtraction, we used the same procedure as the VIS arm to be consistent with the reduction.

2.3. One-dimensional extraction

Due to the small separation between the quasar images A, B, and the lens galaxy, there can be cross-contamination in their spectra (see Fig. 1). To obtain uncontaminated spectra we proceeded as follows. First, we collapsed the 2D reduced spectrum along the wavelength axis in a high S/N region, for example around an emission line region (Hz in the NIR, OIII in VIS, and MgII in the UVB arm). In the case of the VIS and UVB arms, we selected bins of 20 pixels (4 Å) to increase the S/N of the sources. We masked the outliers (persistent bad pixels, poor sky subtraction, and/or low S/N regions) to obtain the best-fit parameters as a function of the wavelength. The spatial contribution of each component was estimated by simultaneously fitting three Gaussian profiles. The distances between image A and B (∼2.87 arcsec ≈14 pixels) and between image A and the lens galaxy projection onto the AB segment (∼1.47 arcsec ≈8 pixels) were used to fix the position of the Gaussian centers for B and the lens galaxy, respectively. Assuming A and B are point sources, we can consider that they have the same full width at half maximum (FWHM) and standard deviation parameter (σ), and a variable σ (larger than σ, due to its extended emission) for the lensing galaxy in the UVB and VIS arms. Due to the faintness of the lens galaxy in the NIR arm, the σ value of the lens galaxy is considered the same as for the images (σ = σ). Thus, the free parameters are the amplitudes, image A center, σ for the point sources (and lens galaxy in NIR), and σ for the lens galaxy (in the UVB and VIS arms). Using the best-fit estimated values and their respective uncertainties, we constructed a probability function for the spatial distribution of each target (quasar images and lens galaxy), allowing us to identify the probability that a given spatial pixel belongs to one of the targets. We used error propagation for each free parameter to estimate the related uncertainties in each final uncontaminated spectrum.

Considering the seeing variation along the wavelength range and the selected slit width, we needed to estimate the percentage of lost flux. We estimated the broadening of the spectra profile due to the instrumental dispersion at different wavelengths by fitting a Gaussian function for each wavelength bin of the telluric standard star (HD 115470 for the case of OB 1 of seeing 0.75′′). The σ obtained was of 0.76′′ with a dispersion that does not vary from 1 pixel between the arms. We used this value (see in Table 1) to calculate the percentage of flux entering the slit by simulating the system as a sum of the Gaussian functions and integrating it within the slit using the seeing delivered in the header. The percentage of flux lost was 30.5% in UVB, 14.9% in VIS, and 19.7% in NIR. These values will be included as an extra flux error in all our analyses.

After extracting the spectra for the three components, we found that the lens galaxy spectrum shows contamination by quasar emission lines. Given the amount of contamination, the slit width and position angle, we infer that this is a contribution from image C (see Fig. 1). To obtain the uncontaminated lens galaxy spectrum, we used spectrum A as a proxy for C and estimated the C contribution fraction for each arm (0.25 for NIR, 0.43 for VIS, 0.5 for UVB) that removes the quasar emission lines. The S/N of the emission line and continuum were obtained by estimating the standard deviation of the background. We used
Table 1. Log of the observation for the three observing blocks.

| OB | Date            | Arm  | Exp. time (s) | Number of Exposures | Airmass | Seeing \(^{(1)}\) (") |
|----|-----------------|------|---------------|----------------------|---------|-------------------------|
| 1  | 9-10 July 2019  | UVB  | 600           | 2                    | 1.067   | 1.02                    |
|    |                 | VIS  | 600           | 2                    | 1.068   | 1.09                    |
|    |                 | NIR  | 600           | 4                    | 1.065   | 1.08                    |
| 2  | 9-10 July 2019  | UVB  | 600           | 2                    | 1.133   | 1.08                    |
|    |                 | VIS  | 600           | 2                    | 1.134   | 1.02                    |
|    |                 | NIR  | 600           | 4                    | 1.127   | 1.01                    |
| 3  | 10-11 July 2019 | UVB  | 600           | 2                    | 1.135   | 1.27                    |
|    |                 | VIS  | 600           | 2                    | 1.134   | 1.30                    |
|    |                 | NIR  | 600           | 4                    | 1.127   | 1.28                    |

Notes. \(^{(1)}\)This seeing corresponds to the delivered seeing on Image Analysis detector given in the header of each frame.

Table 2. FWHM, luminosities, and \(M_{BH}\).

| Image | Line | FWHM [km s\(^{-1}\)] | \(\log_{10}(L_{\text{rest}})/L_\odot\) \(^{(a)}\) | \(\log_{10}(M_{BH})/M_\odot\) | \(\log_{10}(r_f)\) [cm] \(^{(b)}\) | \(S/N\) line \(^{(c)}\) | \(S/N\) continuum \(^{(c)}\) |
|-------|------|----------------------|-----------------------------------------------|-------------------------------|---------------------------------|-------------------|-----------------------|
| A     | Mg\(\beta\) | 3914.52 ± 500.09 | 44.23 ± 0.19 | 8.25 ± 0.59 | 12.5 ± 0.59 | 30 | 5 |
|       | H\(\beta\)    | 4689.32 ± 42.96 | 44.29 ± 0.17 | 8.27 ± 0.24 | 15.26 ± 0.79 | 16 | 6 |
|       | H\(\alpha\)    | 5595.68 ± 125.92 | 44.36 ± 0.20 | 8.57 ± 0.22 | 15.63 ± 0.83 | 73 | 11 |
| B     | Mg\(\beta\) | 4118.73 ± 921.90 | 44.23 ± 0.19 | 8.29 ± 0.88 | 14.95 ± 0.23 | 35 | 6 |
|       | H\(\beta\)    | 4817.63 ± 48.15 | 44.21 ± 0.16 | 8.24 ± 0.21 | 15.23 ± 0.85 | 19 | 6 |
|       | H\(\alpha\)    | 6150.98 ± 133.39 | 44.29 ± 0.23 | 8.61 ± 0.27 | 15.66 ± 0.74 | 85 | 12 |

Notes. \(^{(a)}\)\(L_{\text{rest}}\) = Luminosity (\(L_{5100}, L_{5100}, L_{5100}\)) for Mg\(\beta\), H\(\alpha\) and H\(\beta\) respectively. The luminosity for H\(\alpha\) and H\(\beta\) is from the spectra and for Mg\(\beta\) is obtained from the SED. \(^{(b)}\)\(r_f\) is the accretion disk size obtained from Eq. (5) at the \(L_{\text{rest}}\) of the emission line used for the \(M_{BH}\) measurement. \(^{(c)}\)This is the maximum S/N in the peak of the emission line.

the 2D spectra to obtain the background emission (sky emission in Sect. 2.2), getting the mean and standard deviation of this background. We then chose a continuum region located around the emission line (50 Å) for each signal contribution (image A, B, and the lensing galaxy) and obtained the mean value. With these values we calculated the S/N of the continuum. We calculated the S/N of the emission lines using the same method: selecting the same spatial region, but estimating the mean in a reduced wavelength window (approximately 300–500 Å) around each emission line. The S/N values for the continuum and emission lines are listed in Table 2.

The final spectra for images A, B, and the lensing galaxy (uncontaminated by the quasar emission) are presented in Fig. 4. As the ADC did not work during the night that OB 1 and 2 were taken, the UVB and VIS arm experienced flux loss (Fig. 4), explaining the atypical profile of the AGN spectra (see Vanden Berk et al. 2001 and Glikman et al. 2006 for a composite quasar spectra). This loss will affect the luminosity measurement, specially in the UVB arm (see Sect. 3.1 for more details).

3. Methods

Black hole mass is estimated by using the SE method (e.g., McLure & Dunlop 2004; Shen et al. 2008; Trakhtenbrot & Netzer 2012), which combines the Doppler line width of the broad emission line and the monochromatic luminosity to obtain a proxy for \(M_{BH}\). If we assume that the emitting gas in the BLR is virialized, then

\[
M_{BH} = f R_{BLR} (\Delta v)^2 G^{-1},
\]

where \(G\) is the gravitational constant, \(R_{BLR}\) is the BLR size, \((\Delta v)^2\) is the velocity of the line emitting gas in the BLR, and \(f\) is the virial factor that depends on the unknown structure, kinematics, inclination, and distribution of the BLR (Peterson et al. 2004 and references therein). The BLR size comes from the reverberation mapping (RM, Blandford & McKee 1982; Peterson 1993) and from the known correlation between the AGN luminosity and the size of the BEL, \(R_{BLR} \sim (\lambda L_{\beta})^{\alpha}\) (e.g., Kaspi et al. 2000, 2005; Bentz et al. 2009), allowing us to estimate \(M_{BH}\) as

\[
\log(M_{BH}) = \log(K) + \alpha \log \left( \frac{\lambda L_{\beta}}{10^{44} \text{ erg s}^{-1}} \right) + 2.0 \log \left( \frac{\text{FWHM}}{1000 \text{ km s}^{-1}} \right),
\]

where \(K = G^{-1} f\). The literature shows different values for the parameters \(K\) and \(\alpha\) (McLure & Dunlop 2004; Vestergaard & Peterson 2006; Vestergaard & Osmer 2009; Shen et al. 2011), although we use those estimated by Mejía-Restrepo et al. (2016) because they were estimated using a similar observing setup, thus minimizing the systematic effects. In particular, the sample of Mejía-Restrepo et al. (2016) contains several emission lines for each object; in addition all the lines for a single object were observed simultaneously. The values for the parameters used for the emission lines (H\(\alpha\), H\(\beta\), and Mg\(\beta\)) at their respective luminosities (\(L_{5100}, L_{5100}, L_{5100}\)) are

\[
\log K, \alpha_{H\alpha} = (6.845, 0.650), \quad \log K, \alpha_{H\beta} = (6.740, 0.650), \quad \log K, \alpha_{Mg\beta} = (6.925, 0.609).
\]

In addition to the usual uncertainties related to the SE method (FWHM, luminosity, and \(f\) parameter estimations), the observed source luminosity also needs to be corrected for the lensing magnification. To obtain the magnification factor (\(\mu\)
we use the convergence ($\kappa$) and shear ($\gamma$) parameters estimated from the lens model as $\mu = 1/[1 - (1 - \kappa)^2 - \gamma^2]$ (Narayan & Bartelmann 1996). Employing the values previously calculated by Shajib et al. (2019), we obtain a magnification factor of $\mu_A = 2.27 \pm 0.21$ and $\mu_B = 2.71 \pm 0.32$.

### 3.1. Emission line fitting and luminosity measurement

After demagnifying the spectra, and removing the continuum and the iron template (following Mejía-Restrepo et al. 2016), we modeled each emission line profile and estimated the BEL FWHM. We used Gaussian functions to represent the broad and narrow components of each emission line (see Table 4 of Shang et al. 2007) and masked those regions affected by absorptions. In the Hα region we added four extra Gaussians for the [N II] and [S II] narrow-line region (NLR) doublets. In the Hβ region we considered two extra Gaussians for the [O III] NLR doublet and one for the He II broad emission line. For the Mg II region we considered two narrow and two broad components. The FWHM used for the $M_{\text{fit}}$ measurement was obtained from the standard deviation of line profile after removing the NLR component (i.e., the resulting profile is the combined Gaussians representing the broad line components). The uncertainties were obtained using error propagation and a Monte Carlo simulation of 1000 random resamplings, assuming a Gaussian distribution for the flux uncertainty at each pixel. The best line fit is shown in red in Fig. 5. As every emission line exhibits some kind of distortion (possible absorptions) that could lead to an overestimation of their FWHM, we decided to mask those regions for the Gaussian fitting. The Mg II profile has several absorption features (masked regions [2787:2794, 2796:2802] Å), possibly caused by the circumgalactic medium (CGM). In the case of Hγ the feature perceived as absorption masked region [6525:6547, 6569:6576] Å could instead be a very bright NLR. Similarly, Hβ shows a distorted profile (masked region [4835:4849, 4866:4878] Å) possibly related to a poor FeII fitting. The monochromatic luminosity was measured using continuum windows on each side of the emission line ([4670: 4730, 5080: 5120] Å for Hβ and [6150: 6250, 6800: 6900] Å for Hα). These spectral windows were selected for the low (or even null) emission line contamination levels, and were used to interpolate the region of interest following a single power-law function. As mentioned above, the flux loss in the UVB and VIS arms impede the use of the spectra to estimate the monochromatic luminosity at 3000 Å. Instead, we estimated this luminosity by fitting a spectral energy distribution (SED) template of Assef et al. (2010) to the unmagnified magnitudes obtained from HST (Shajib et al. 2019) and DES (Agnello et al. 2018). Compared to the luminosity measurement, the FWHM of Mg II FWHM is not affected by this flux loss. The FWHM obtained from the line profile fitting and the monochromatic luminosity (estimated from the continuum and SED) for each emission line in image A and B is presented in Table 2.

### 3.2. Microlensing analysis

Microlensing can induce flux variations in the quasar images due to lensing from stars in the lensed galaxy halo (e.g., Chang & Refsdal 1979; Schneider et al. 2006). This flux variation in one or more images is sensitive to the angular size of the source, meaning that the magnification will be bigger for a smaller emitting region. In this situation, we could study the inner structure of WGD2038-4008 from the SE images of different observations, where the accretion disk and BLR can be affected differently by microlensing and could affect the wings of the emission lines. On the contrary, the NLR is insensitive to microlensing and can be used as the baseline (Abajas et al. 2002). To investigate
Fig. 5. Gaussian fitting of Hα, Hβ, and MgII regions for images A (left) and B (right). The red line represents the best fit, the black lines represent the different components of each region (emission and absorption), the green line represents the Fe template, and the blue line is the continuum fit of the spectra. The 1σ error of the spectra along with the residuals and their respective errors are at the bottom of the images.
whether microlensing is present, we use the magnitude difference between the emission line core and the continuum (see Moustakas & Metcalf 2003; Mediavilla et al. 2009, 2011; Motta et al. 2012, 2017; Guerras et al. 2013; Rojas et al. 2020). The quasar emission lines have different components, meaning that they come from different inner regions of the AGN. The line core is dominated by the NLR, while the wings are dominated by the BLR from different regions are line between two regions on each side of each emission line. The difference between components in the continuum by fitting a straight line between two regions to obtain the continuum flux for both images. This error in the spectra and the straight line are added in quadrature. The velocity dispersion ($\sigma$) of a galaxy measures the random motion of stars due to a presence of a mass. Obtaining an accurate dispersion value is important to restrict the lens model parameters, and together with the light curves of the images of the lensed quasar measure the Hubble constant $H_0$ and helps to improve the uncertainties. The velocity dispersion was estimated from the lens galaxy spectrum using the penalized pixel-fitting (pPXF; Cappellari & Emsellem 2004; Cappellari 2017). We used the rest-frame wavelength 3600–4200 Å for the UVB arm and 4800–5800 Å for the VIS arm. The spectra were fitted using the Single Stellar Population library by Vazdekis et al. (2010) included in pPXF (see Fig. 6). The velocity dispersion obtained was 299 ± 12 km s$^{-1}$, consistent with the measurements of Buckley-Geer et al. (2020) (296 ± 19 km s and 303 ± 24 km s using Gemini South/GMOS-S spectra).

4. Results

We identified the three most prominent emission lines of the lensed quasar (MgII, H$\beta$, and H$\alpha$) with high S/N (see Table 2). The spectra were demagnified using the parameters from the lens model of Shajib et al. (2019) and the continuum was subtracted to compare the profiles of image A and B (Fig. 7). Interestingly, we find an enhancement of the right wing of H$\alpha$ emission line of image B compared to image A (between ∼6600 and 6700 Å). This magnitude difference (∼0.28 ± 0.03 mag integrated in the region [6591.4:6686.5] Å) could be explained assuming that microlensing is affecting the H$\alpha$ broad emission line. This effect should also be seen in the H$\beta$ profile as it arises from a region of similar size to H$\alpha$. However, we do not detect this effect, although this could be due to the low S/N of H$\alpha$ ($S/N$ ≤ 20) compared to H$\alpha$ ($S/N$ ≥ 72) and to the presence of absorption-like features. There is no sign of this effect in the MgII profile ($S/N$ ≤ 31), which is reasonable because MgII emission is produced in a region farther away than the Balmer lines (Goad et al. 2012), and hence is less susceptible to microlensing effects.

Multi-Gaussian fitting of images A and B are shown in Fig. 5 following the procedure described in Sect. 3.1. The gray shaded regions represent the masked sections used during the fitting. Table 2 shows the FWHM estimated for each broad emission line in each quasar image. Even though the components of MgII have slightly different amplitudes, probably due to the absorptions that are contributing to the profile, the FWHM values are within the errors. The FWHM of H$\beta$ is in good agreement in spite of the low S/N. In the case of H$\alpha$, the estimated FWHM is different (∼5σ) and we discuss below how this might affect our $M_{\text{BH}}$ estimations. To investigate whether microlensing is present in the continuum, we obtained the magnitude difference between the core of each emission line uncontaminated by the continuum, ($m_A - m_B$)$_{\text{line}}$ and the continuum under the emission line, ($m_A - m_B$)$_{\text{cont}}$, shown in Fig. 8. The H$\alpha$ emission line region shows two values corresponding to two emission line peaks, avoiding the right wing (see Fig. 7), integrated in the windows [6500.1:6526.0, 6547.7:6565.4] Å. The H$\beta$ region shows three values corresponding to H$\beta$ ([4820:4890] Å integration window) and the [OIII] doublet emission line cores ([4949.2:4960.0, 4996.4:5007.0] Å integration window). We included the MgII region integrated between [2774.6:2784.1] Å and Paschen [9512.0:9533.0] Å. Considering that the magnitude difference in the emission lines is approximately constant, we use the median and its standard error, ($m_A - m_B$)$_{\text{line}}$ = 0.17 ± 0.05 mag, as our baseline of no-microlensing. As the values for the integrated continuum also yield a roughly constant value along the wavelength, we use the median to estimate ($m_A - m_B$)$_{\text{cont}}$ = 0.01 ± 0.03 mag. We compare our result with spectroscopic data of the integrated flux obtained by Nierenberg et al. (2020) (see Fig. 8) ($m_A - m_B$)$_{\text{cont}}$ = −0.06 ± 0.09 and ($m_A - m_B$)$_{\text{line}}$ = 0.16 ± 0.02 mag, which is in agreement with our magnitude difference for the continuum and emission line in the H$\beta$ region, respectively. Published data from broadband photometry taken between 2016 and 2017 is also included in Fig. 8 (Agnello et al. 2018; Lee 2019; Shajib et al. 2019). We fit a median function to these values obtaining ($m_A - m_B$)$_{\text{int}}$ = 0.21 ± 0.06 mag. The values are in agreement with the core of our narrow emission lines.

Fig. 6. Fit of stellar templates to the lensing galaxy using pPXF package after removing the extra quasar contribution.
Since the above-mentioned data are not time-delay corrected, the magnitude difference estimated from our spectra, $\Delta m = (m_A - m_B)_{\text{cont}} - (m_A - m_B)_{\text{line}} = -0.16 \pm 0.06$ mag, could be due to intrinsic variability coupled with a time lag between the images. We use the Yonehara et al. (2008) procedure to estimate this effect. We assume the structure function inferred from the imaging data of quasars (Vanden Berk et al. 2004), an absolute magnitude range for the source in I band, $M_I = (-21, -30)$, the predicted time delay for the quasar images $\Delta t_{AB} = -6 \pm 1$ days (Shajib et al. 2019), and assume no lag between our observations as they were obtained with 1 day of difference. We obtained a magnitude difference induced by time delay coupled with intrinsic variability of 0.05 mag (0.03 mag) to 0.07 mag (0.04 mag) for a $-21$ mag ($-30$ mag) source in the F160W and F475W broadband filters, respectively. On the other hand, we also use light curves obtained by COSMOGRAIL (e.g., Bonvin et al. 2017; Courbin et al. 2011; Eigenbrod et al. 2005), which has a monitoring program to obtain time delay between multiple images of lensed quasars. WGD2038-4008 follow-up is carried out in MPAI 2.2m telescope (La Silla Observatory, Chile) with an average of one measurement per week (F. Courbin, priv. comm.), although no time delay has been measured yet. We considered three dates that were seven days apart and within two weeks of our X-shooter observations, then shift the B data to correct by time delay, and estimate the average magnitude difference as $(m_A - m_B)_{\text{cont}} \sim 0.16 \pm 0.03$ mag. This value is in good agreement with our estimation using the core of the emission lines. Therefore, $\Delta m = -0.16 \pm 0.06$ mag seems to indicate the presence of a constant or long-lasting microlensing event not detected by the light curves (Sluse & Tetev 2014). To investigate this possibility, we estimate the timescale associated with such event. Following Treyer & Wambsganss (2004), we define two timescales: the standard lensing time ($t_L$), and the crossing time ($t_c$). The first represents the time it takes a star to cross a length equivalent to the Einstein radius

$$t_L = (1 + z_L)R_E/v_L,$$  
(3)

where $z_L$ is the lens redshift, $R_E$ the Einstein radius in the source plane, and $v_L$ the effective source velocity (Treyer & Wambsganss 2004). The second timescale refers to the time, within the length of an Einstein radius, when the source may encounter a caustic line, causing a large magnification

$$t_c = (1 + z_L)R_{\text{source}}/(v_L(D_S/D_L))$$  
(4)

where $R_{\text{source}}$ is the quasar size (i.e., the accretion disk size, $\log_{10}(r_*/\text{cm}) = 15.65$), and $D_S$ and $D_L$ the angular diameter distance (Hogg 1999) of the observer-source and observer-lens, respectively, with our assumed cosmology. Considering a typical value of $v_L = 600 \text{ km s}^{-1}$ as assumed by Treyer & Wambsganss (2004), we estimate $t_L \approx 27.7$ years and $t_c \approx 0.6$ year. On the other hand, if we calculate the effective source velocity following Mosquera & Kochanek (2011), we obtain $v_{\text{eff}} = 820 \text{ km s}^{-1}$, which yields $t_L \sim 20.3$ years and $t_c \approx 0.5$ year, respectively. Thus, a long-lasting microlensing event would last for $\sim 20$ years, while the crossing time should be around 6 months.

In spite of this microlensing magnification, the induced error in the luminosity is negligible as the majority of the error budget is introduced by the macro model magnification (Sect. 3).

The monochromatic luminosity at $L_{5100}$ was estimated using a single power-law function between two continuum windows on each side of the BELs. It agrees for H$\alpha$ and H$\beta$ of each image, within the errors, with an average value of $R_{\text{source}} = R_{\text{source}}/v_L$ and $\Delta L = \Delta L/v_L$, where $v_L$ is the effective velocity and is defined as a combination of the motions of the observer, the lens, and the source.

Fig. 7. Mg II, H$\beta$, and H$\alpha$ emission line region. The images are demagnified using the magnification values given in Sect. 3.

Fig. 8. Magnitude difference $m_A - m_B$ vs. $\lambda_0$ between images A and B. The red squares show the integrated continuum and the black circles the emission line core without the continuum using X-shooter. Shown are the measurements obtained from the literature: HST (Shajib et al. 2019) (magenta triangles), VISTA (Lee 2019) (cyan diamonds), DES (Agnello et al. 2018) (blue diamonds) and HST F105W/G102 (Nierenberg et al. 2020) (orange square for continuum and orange triangle for a narrow emission line). The red line is the median of the continuum, the dotted red line the standard deviation, the black line the emission line core, and the blue line the literature.
log₁₀(L₁₅₀₀₀/L₆₅₆₅) = 44.29 ± 0.03. Due to flux loss in UVB, we modeled a SED to estimate L₃₀₀₀ using the magnitudes and
magnification of image A, obtaining log₁₀(L₃₀₀₀/L₆₅₆₅) = 44.23 ± 0.19.

The luminosities L₃₀₀₀ and L₅₁₀₀ agree within their errors, even
though they were obtained with different methods. The MBH
was obtained following Eq. (2) with an average value between
images A and B of log₁₀(MBH/M₆₅₆₅) = 8.59 ± 0.35, 8.25 ± 0.32,
8.27 ± 1.06 for Hα, Hβ, and MgII, respectively. The MBH
estimates obtained using the three different emission lines are con-
sistent within 2σ. We show the MBH estimations along with
those of the literature of lensed quasars in Fig. 9. To avoid the
discrepancies associated with the different parameter values used
by the authors, we combine their FWHM and monochromatic luminosity
values using Eq. (2) to obtain M BH. We converted from intrinsic to bolometric luminosity applying Lbol = A Lref,
where A = (3.81, 5.15, 9.6) for Lref = (L₁₅₀₀, L₃₀₀₀, L₅₁₀₀) pre-
sented in Sluse et al. (2012). MBH estimates for 33 lensed quasars
are also included in Fig. 9 (some of them have several values as
they are obtained from different emission lines) as well as those
of Shen et al. (2019) for non-lensed quasars from SDSS reverber-
ation mapping. The figure shows that our results for image A and
B of WGD2038–4008 are in good agreement with those of the
non-lensed quasars, situating our object in the low-luminosity
range of the diagram.

We can also infer the accretion disk size (rₐ) assuming a thin-
disk model (Shakura & Sunyaev 1973) and considering our MBH
estimate (Mosquera & Kochanek 2011) as

\[ rₐ = 9.7 \times 10^{15} \left( \frac{L_{bol}}{\mu \mu m} \right)^{4/3} \left( \frac{M_{BH}}{10^9 M_\odot} \right)^{2/3} \left( \frac{L}{n_L} \right)^{1/3} [\text{cm}] \] (5)

Here \( L_{bol} \) is the wavelength where the M BH is measured, \( n \) is the accretion efficiency, and \( L/L_E \) the luminosity in units of the
Eddington luminosity. For a typical accretion rate \( \eta = 0.1 \) and
\( L/L_E \sim 1/3 \) (Schulze & Wisotzki 2010). Using the different
M BH estimates with the wavelength value at Hα, Hβ, and MgII,
the accretion disk size measurements are shown in Table 2. The
size of MgII is on average log₁₀(rₐ/cm) = 14.98 ± 0.84, Hβ is
15.25 ± 0.4, and Hα 15.67 ± 0.74. Our estimates are in agree-
ment with each other and with Morgan et al. (2018). We scaled
our wavelength (\( \lambda \) in which the M BH was measured) to 2500 Å,
assuming \( rₐ \propto \lambda^{1/3} \) and obtained log₁₀(rₐ/cm) = 14.94 ± 0.22,
15.25 ± 0.82 and 15.65 ± 0.79 in MgII, Hβ, and Hα, respec-
tively. These values are consistent with the theoretical values
estimated by Morgan et al. (2018) at r₁₅₀₀: 15.41 ± 0.15 for MgII,
15.37 ± 0.26 for Hβ, and 15.62 ± 0.18 for Hα.

5. Conclusions

We obtained high S/N observations for the quadruple lensed sys-
tem WGD2038–4008 using the X-shooter instrument at VLT. We
used Gaussian fitting to obtain uncontaminated spectra for the
A and B lensed quasar images and the lens galaxy. The most
prominent emission lines were detected (MgII, Hβ, and Hα) as
well as the absorption lines in the lensing galaxy. We confirmed
the velocity dispersion of the lensing galaxy spectra, obtaining
299 ± 12 km s⁻¹, in agreement with previously estimated values
(2.96 ± 19 km s⁻¹) (Buckley-Geer et al. 2020).

The magnification factors were estimated from the lens
parameters of Shahjib et al. (2019) (\( \mu_A = 2.27 ± 0.21 \) and
\( \mu_B = 2.71 ± 0.32 \)) and were used to demagnify the spectra.
Comparing the continuum-subtracted emission lines, we find that
there is an enhancement in the right wing of Hα of image B
that could be due to microlensing. However, this effect is not seen
in Hβ (a region similar in size to Hα) but this might because
of the low S/N and to the presence of absorption-like features.
The MgII profile does not show any sign of microlensing, and
it could be because it is produced in a region that is farther
away. Magnification in the red wing of the Hα broad emission
line has been detected in HE0435-1223 (Braibant et al. 2014)
and QSO2237+0305 (Braibant et al. 2016). The main conclu-
sion is that these line profile distortions can be explained by
the differential magnification of a Keplerian disk model. As
the continuum region is expected to be smaller than the BLR,
the profile distortions are also accompanied by larger magni-
fication of the continuum. However, in our case the magnifi-
cation in the continuum is smaller than that in the Hα broad
emission line. On the other hand, several papers describe an
enhancement in the Fe Kα profile with higher magnification than
the X-ray continuum in MG J0414+0534 (Chartas et al. 2002),
QSO 2237+0305 (Dai et al. 2003), and H1413+117 (Chartas
et al. 2004). This effect is attributed to differential micro-
lensing. Popović et al. (2003), who use a standard accretion disk
and caustic crossing to investigate the structure that could lead to
such differences, conclude in Popović et al. (2006) that different
dimensions for the emitting region (e.g., an inner BEL anulus
cosmic radius smaller than the continuum disk) and the segrega-
tion of emitters allow the reproduction of the Fe Kα enhancement
without an equivalent amplification of the continuum. Furthermore,
Abajas et al. (2007) demonstrated that this result could also be
obtained in the case of a biconic model for the BEL. Thus, a
similar effect might be used to explain our results, but a further
analysis is needed to confirm this.

The FWHM was measured for the three emission lines and are
in agreement for Hβ and MgII for both images. Even though
Hα has a discrepancy in the right wing, we measured the FWHM
for both of them (with a difference of >5σ).
The microlensing effect in the continuum was investigated obtaining the magnitude difference for the continuum (0.01 ± 0.03 mag) and the core of the emission lines (0.17 ± 0.05 mag). Our values are in agreement with spectroscopic data from Nierenberg et al. (2020) and with photometric data corrected by time-delay. There seems to be a microlensing effect in the continuum of Δm = −0.16 ± 0.06 mag.

The monochromatic luminosity at 5100 Å was obtained for Hα and Hβ using a single power-law function to the region of interest. The luminosities for both images are in good agreement, with a mean of log 10(L/Hα/L⊙) = 44.29 ± 0.20. On the other hand, L3000 was estimated using SED and obtained log 10(L3000/L⊙) = 44.23 ± 0.19. Both luminosities are in agreement within the errors.

The M_BH was measured with the luminosity and the FWHM from the broad emission lines, obtaining a consistent mass for both images in the same BEL and a mean mass of log 10(M_BH/M⊙) = 8.37 ± 0.40 for this quadruple lensed quasar. When combined with the quasar’s monochromatic luminosities, we find Eddington ratios similar to those measured in the literature for unlensed low-luminosity quasars. Finally, we obtained the accretion disk size from Eq. (5), obtaining an average size of log 10(r_ac/cm) = 15.28 ± 0.63.

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