Restframe UV-to-optical spectroscopy of APM 08279+5255
BAL classification and black hole mass estimates

F. G. Saturni1,2, M. Bischetti1,3, E. Piconcelli1, A. Bongiorno1, C. Cicone4, C. Feruglio5, F. Fiore1, S. Gallerani6, M. Giustini7, S. Piranomonte1, G. Vietri1,8,9, and C. Vignali10,11

1 INAF – Osservatorio Astronomico di Roma, Via Frascati 33, 00040 Monte Porzio Catone (RM), Italy
e-mail: francescogabriele.saturni@oa-roma.inaf.it
2 Space Science Data Center, Agenzia Spaziale Italiana, Via del Politecnico snc, 00133 Roma, Italy
3 Dip. di Fisica, Università degli Studi di Roma “Tor Vergata”, Via della Ricerca Scientifica 1, 00133 Roma, Italy
4 INAF – Osservatorio Astronomico di Brera, Via Brera 28, 20121 Milano, Italy
5 INAF – Osservatorio Astronomico di Trieste, Via G. B. Tiepolo 11, 34143 Trieste, Italy
6 Scuola Normale Superiore, Pzza dei Cavalieri 7, 56126 Pisa, Italy
7 SRON – Netherlands Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands
8 Excellence Cluster Universe, Technische Universität München, Boltzmannstr. 2, 85748 Garching b. München, Germany
9 European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching b. München, Germany
10 Dip. di Fisica e Astronomia, Alma Mater Studiorum, Università degli Studi di Bologna, Via P. Gobetti 93/2, 40129 Bologna, Italy
11 INAF – Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Via P. Gobetti 93/3, 40129 Bologna, Italy

Received 8 February 2018 / Accepted 24 April 2018

Abstract

We present the analysis of the restframe optical-to-UV spectrum of APM 08279+5255, a well-known lensed broad absorption line (BAL) quasar at \( z = 3.911 \). The spectroscopic data were taken with the optical DOLoRes and near-IR NICs instruments at TNG, and include the previously unexplored range between C\( \text{III}\)\( \lambda 1910 \) and [O \( \text{III}\)]\( \lambda 4959,5007 \). We have investigated the possible presence of multiple BALs by computing “bailyness” and absorption indexes (i.e., BI, BI\(_\text{H}\), and AI) for the transitions Si \( \text{IV}\)\( \lambda 1400\), C \( \text{IV}\)\( \lambda 1549\), Al \( \text{III}\)\( \lambda 1860\), and Mg \( \text{II}\)\( \lambda 2800\). No clear evidence for the presence of absorption features is found in addition to the already known, prominent BAL associated to C \( \text{IV}\), which supports a high-ionization BAL classification for APM 08279+5255. We also studied the properties of the [O \( \text{III}\)], H\( \beta\), and Mg \( \text{II}\) emission lines. We find that [O \( \text{III}\)] is intrinsically weak (\( \text{F}_{\text{OIII}} / \text{F}_{\text{Hβ}} \leq 0.04 \)), as it is typically found in luminous quasars with a strongly blueshifted C \( \text{IV}\) emission line (~2500 km s\(^{-1}\)) for APM 08279+5255. We computed the single-epoch black hole mass based on Mg \( \text{II}\) and H\( \beta\) broad emission lines, finding \( M_{\text{BH}} = (2 \pm 3) \times 10^{9} M_{\odot} \) with the magnification factor \( \mu \) that can vary between 4 and 100 according to CO and restframe UV-to-mid-IR imaging respectively. Using a Mg \( \text{II}\) equivalent width (EW)-to-Eddington ratio relation, the EW\(_{\text{MgII}} \sim 27 \) \( \AA \) measured for APM 08279+5255 translates into an Eddington ratio of \( \sim 0.4 \), which is more consistent with \( \mu = 4 \). This magnification factor also provides a value of \( M_{\text{BH}} \) that is consistent with recent reverberation-mapping measurements derived from C \( \text{IV}\) and Si \( \text{IV}\).

Key words. galaxies: active – quasars: general – quasars: absorption lines – quasars: emission lines – quasars: supermassive black holes – quasars: individual: APM 08279+5255

1. Introduction

APM 08279+5255 is a well-known luminous broad absorption-line quasar (BAL QSO) at \( z = 3.911 \). Serendipitously discovered in a Galactic survey for cold carbon stars (Irwin et al. 1998), it is archetypal to several categories of the quasar class, showing together many of the observational phenomena that can be found in such objects. In fact, beyond having evidence of both broad (Srianand & Petitjean 2000) and intrinsic narrow (Ellison et al. 2004) absorption features associated with the C \( \text{IV}\)\( \lambda 1549 \) emission line, it also shows an uncommon O \( \text{VI}\)\( \lambda 1030 \) BAL embedded in the Ly\( \alpha \) forest (Hines et al. 1999) and an X-ray ultra-fast outflow (UFO) associated to highly-ionized iron (Hasinger et al. 2002; Chartas et al. 2002; Saenz et al. 2009; Hagino et al. 2017). Furthermore, its high-ionization emission lines, from Ly\( \alpha \) to C \( \text{III}\)\( \lambda 1910 \), are characterized by a significant blueshift of ~2500 km s\(^{-1}\) with respect to molecular (Downes et al. 1999) and Balmer lines (Oyabu et al. 2009). A blueshifted emission component with \( v \sim 800 \) km s\(^{-1}\), corresponding to a molecular outflow, is also detected in the CO(4 \( \rightarrow \) 3) transition by Feruglio et al. (2017) through 3.2 mm observations with the NOEMA interferometer.

The source APM 08279+5255 is gravitationally lensed (Ledoux et al. 1998) by an unobserved galaxy at \( z \sim 1 \) (Petitjean et al. 2000; Ellison et al. 2004). The lensed image is elongated in the NE direction and consists of three components, with a maximum separation of \( 0^\prime\prime35 \pm 0^\prime\prime02 \) (Ledoux et al. 1998). This makes APM 08279+5255 the first confirmed case with an odd number of images (Ibata et al. 1999; Lewis et al. 2002b). The lack of knowledge about the lensing object further complicates the estimation of the magnification factor \( \mu \). Current lens models are built on the observation of the CO(1 \( \rightarrow \) 0) molecular line (e.g., Lewis et al. 2002a), but the resulting \( \mu \) is strongly dependent on the lens geometry, ranging from \( \mu \sim 4 \) (highly-inclined spiral galaxy; Riechers et al. 2009) up to \( \mu \sim 100 \)
Since its discovery, several photometric and spectroscopic observational campaigns have targeted APM 08279+5255 in different energy bands. Both short-term and long-term monitoring of this object have been performed for a wide range of purposes, from the analysis of its optical variability (Lewis et al. 1999) to the study of the UFO through photoionization codes (Saez & Chartas 2011), the investigation of the C iv absorption variability (Trevese et al. 2013; Saturni et al. 2014) and the reverberation mapping (Trevese et al. 2007; Saturni et al. 2016). In particular, the variability study of APM 08279+5255 absorption systems (Trevese et al. 2013; Saturni et al. 2014, 2016) concluded that the C iv absorption variability in APM 08279+5255 is most likely driven by changes in the photoionization state of the gas, responding to variations of the C iv ionizing continuum level.

Single-epoch observations of APM 08279+5255 include restframe UV high-resolution spectroscopy with Keck/HIRES (Ellison et al. 1999) and HST/STIS (Lewis et al. 2002b) for the study of the damped Lyα absorbers (DLAs) and intervening absorption systems (Petitjean et al. 2000; Ellison et al. 2004). Srianand & Petitjean (2000) first analyzed the high-velocity absorption system blueward the C iv emission peak thanks to the availability of the Keck/HIRES spectrum, finding narrow absorption lines embedded between two unresolved broad components. Using the same spectrum, Ellison et al. (2004) studied the resolved absorption feature on the C iv red wing, classifying it as a system of four intervening clouds located close to the quasar systemic redshift.

In this paper, we present the quasi-simultaneous restframe optical-to-ultraviolet (UV) spectrum of APM 08279+5255 taken at the 3.5 m Telescopio Nazionale Galileo (TNG) in La Palma (Canarian Islands) with the Device Optimized for Low Resolution (DOLoRes; ∆λ/λ ∼ 700) and the Near-Infrared Spectrograph and Camera (NICS; ∆λ/λ ∼ 500). Covering the region between C m and [O m] λλ4959,5007 which was unobserved so far, this broadband spectrum allows the study of the restframe wavelength range ∆λ ∼ 1000–5000 Å in a single state of quasar activity. In fact, the interval of 76 days between the near-infrared (NIR) and optical observations corresponds to a restframe interval of ∼15 days, much shorter than typical variability timescales of APM 08279+5255 (∼430 restframe days for continuum flux changes; e.g., Saturni et al. 2016). The paper is organized as follows: we describe the observations and the procedure of data reduction in Sect. 2; we analyze the spectral features in Sect. 3; finally, in Sect. 4 we present single-epoch mass estimates of the supermassive black hole (SMBH) hosted in APM 08279+5255, and discuss our results in Sect. 5. Throughout the text, we report all errors at 1σ confidence level, and adopt a concordance cosmology with H₀ = 70 km s⁻¹ Mpc⁻¹, ΩM = 0.3 and ΩΛ = 0.7.

2. Observations and data reduction

Observations of the APM 08279+5255 restframe optical-to-UV spectrum were carried out on 2011 February 19–20 (optical) and 2011 May 05 (UV) at TNG. The restframe UV spectrum of APM 08279+5255 was obtained with the R-band grism (wavelength range ∆λ4470–10703 Å, dispersion of 2.61 Å px⁻¹, ∆λ/λ = 714) of the DOLoRes instrument, coupled to the 1″ slit. The restframe optical spectrum was acquired with the NICS instrument in two low-resolution configurations, respectively for the IJ (wavelength range ∆λ9000–14 500 Å, dispersion of 5.5 Å px⁻¹, ∆λ/λ = 500) and HK (wavelength range ∆λ14 000–25 000 Å, dispersion of 11.2 Å px⁻¹, ∆λ/λ = 500) bands, with the same slit width of the R-band spectrum.

The restframe UV spectrum ∆λ1020–1870 Å considered in our analysis extends over the observed wavelength interval ∆λ ∼ 5000–9200 Å. A large contamination due to overlap of higher spectral orders is visible redward ∆λ = 9200 Å. The spectrum was calibrated with standard IRAF procedures, and was cleaned from the major telluric absorptions, namely the Fraunhofer A and B bands and the H₂O features, adopting the method described in Trevese et al. (2013). The total restframe optical spectrum extends over the observed wavelength intervals ∆λ ∼ 8700–14 500 Å (IJ bands) and ∆λ ∼ 13 500–24 700 Å (HK bands), corresponding to ∆λ1770 5030 Å in the restframe UV-to-optical bands. A standard NICS observing sequence consists of exposures at two different dither positions (A and B) and taken in the pattern ABBA. Background subtraction was obtained performing A–B and B–A image differences, obtaining four positive aperture images. The spectrum was extracted for each differential image in a standard way using the IRAF task apall. Then, in order to remove cosmic rays, the four extracted spectra were combined together. Finally, a telluric standard star was used to correct the target spectrum for the atmospheric transmission.

In producing the joint APM 08279+5255 UV-to-optical spectrum, we compared the restframe UV flux with a coeval spectrum taken in April 2011 at the Asiago observatory (Italy) for a reverberation-mapping campaign of luminous quasars (Trevese et al. 2007, 2014; Saturni et al. 2016). We noted that the TNG UV flux level obtained from standard-star calibration was a factor ∼1.1 lower than the Asiago spectrum, which was acquired together with a reference star within a wide (8′′) slit in order to not generate differential light losses and be therefore able to construct meaningful light curves (see e.g., Kaspi et al. 2007, for a discussion). We suspected that a light loss happened in acquiring the TNG/DOLoRes spectrum due to a seeing-limited observation rather than diffraction-limited (seeing at La Palma site of up to ∼1″5, to be compared with the 1″ slit width). Additionally, no IR photometric standard stars were available during the NICS observing night. Therefore, we decided instead to recalibrate the APM 08279+5255 full spectrum to the photometry reported in Egami et al. (2000), Ojha et al. (2009).
Calibrated spectrum of APM 08279+5255 before (green dashed line) and after dereddening (black solid line), with corresponding 1σ uncertainty (gray band) – see Sect. 2. Superimposed to the data, the composite quasar template obtained by matching the Vanden Berk et al. (2001) and Glikman et al. (2006) templates around λ ∼ 3000 Å in the restframe (red line) is shown. The continuum level is marked as a black dotted line with slope −1.54. A residual telluric absorption is still present between λ ∼ 17 500 Å and 20 000 Å (cyan shaded area), hence this spectral interval is excluded from the present analysis.

We checked that the magnitudes of APM 08279+5255 used in the recalibration were measured in epochs in which the quasar continuum is not varying. The near-infrared magnitudes are taken at MJD = 51 089 (Egami et al. 2000), whereas the optical photometry is measured in runs between MJD = 53 440 and 54 124 (Ojha et al. 2009). Comparing these epochs with those of the R-band photometric observations used to construct the light curve of APM 08279+5255 in Trevese et al. (2013) and Saturni et al. (2016, see their Fig. 2), we note that they fall in periods during which the observer-frame optical flux of the quasar remains constant within 0.04 mag. Therefore, our photometry-based spectral recalibration is free of biases introduced by spectral variability.

In order to remove the dust reddening, the spectrum was further de-reddened according to a Small Magellanic Cloud (SMC) extinction law (Pei 1992) with A_V = 0.6 (Petitjean et al. 2000) at z = 1.062, i.e., the probable redshift of the lensing galaxy (Ellison et al. 2004). Figure 1 shows the comparison of the joint restframe optical-to-UV spectrum of APM 08279+5255 taken at TNG with a template obtained by matching the Vanden Berk et al. (2001) and the Glikman et al. (2006) SDSS broad-line quasar templates around λ ∼ 3000 Å in the restframe, and normalized to match the observed flux at 1350 Å in the restframe. In our procedure, we have not accounted for the intrinsic reddening of the host galaxy (e.g., Gallerani et al. 2010). In general, BAL QSOs appear in fact to be more reddened by intrinsic dust with respect to normal quasars (see e.g., Richards et al. 2003, and refs. therein), with a BAL QSO fraction rising up to ∼40% in extremely reddened objects (e.g., Urrutia et al. 2009). However, the comparison of our de-reddened spectrum with the joint quasar template (which is in turn used in the following to compute the indexes of absorption for APM 08279+5255) provides no evidence for intrinsic dust reddening within the host galaxy. We thus prefer to consider only the reddening from the lensing galaxy, although we cannot rule out a possible contribution from the APM 08279+5255 host.

3. Analysis of the UV and optical spectral feature

3.1. Absorption features

The restframe UV-to-optical spectrum of APM 08279+5255 is suitable to study the presence of broad absorption features other than those associated to C IV. To this purpose, we calculate the indexes of absorption most commonly used to identify and classify BAL QSOs, namely the “balnicity” index (BI; Weymann et al. 1991), the zero-velocity balnicity index (BI_0; Gibson et al. 2009) and the absorption index (AI; Trump et al. 2006). We performed this calculation for both the high- and low-ionization transitions that most frequently produce absorption in this class.
The mathematical expression of the BI, BI, and AI can be generalized into an integral quantity $I(k)$, where $k = (k_{I-3})$ represents a set of parameters that define the integration limits, the minimal depth and the minimal velocity width of the absorption. We call $I(k)$ the generalized index of absorption, and define it as follows:

$$I(k) = -\int_{-\infty}^{\infty} \left[ 1 - \frac{f(v)}{0.1 k} \right] C(k_4, k_5) \, dv,$$

(1)

where $f(v)$ is the normalized QSO flux in the velocity space, and $C(k_4, k_5)$ a constant assuming unitary value over absorbed regions in which the integrand function is positive, provided that the integrand itself remains greater than 0.1$k$ in contiguous portions of the absorption trough at least $1000k$ km s$^{-1}$ wide (otherwise, $C = 0$). Within this scheme, the set $k$ uniquely identifies each index of absorption: $k_{BI} = (1, 0, 9, 0, 2)$, $k_{BI_0} = (0, 0, 9, 3, 2)$, and $k_{AI} = (0, 1, 10, 1, 1)$. To compute these indexes, we normalized the dereddened APM 08279 spectrum to the joint quasar template from Vanden Berk et al. (2001) and Glikman et al. (2006) shown in Fig. 1, then evaluating the BI, BI_0, and AI according to Eq. (1).

The formal error $\sigma_I^2(k)$ associated to $I(k)$ is connected to the rms error on the flux $\sigma f(v)$ by

$$\sigma_I^2(k) = -\int_{-\infty}^{\infty} \left[ 1 - \frac{f(v)}{0.1 k} \right]^2 C(k_4, k_5) \, dv,$$

(2)

although the real uncertainty is usually dominated by systematic

is in the continuum placement (Trump et al. 2006). Therefore, we adopt a Monte Carlo simulation approach to give a proper evaluation of the uncertainties associated to each nonzero index, or provide fiducial upper limits. Accordingly, we alter the spectrum by adding random noise with Poissonian distribution to each spectral bin, which is assumed to be the mean value of the noise distribution at its wavelength. We then recompute $I(k)$ on this altered spectrum, iterating the process 10 times to reach statistical significance. Finally, we take the standard deviation of the $I(k)$ posterior distribution as the uncertainty to be associated to a nonzero index on the true spectrum. In case of null indexes, we set this standard deviation as the upper limit on the absorption strength. This procedure succeeds in producing fiducial uncertainties or upper limits for all the indexes of absorption but the BI_0 for Si iv, Al iii, and Mg ii. This can be explained in terms of the conservative definition of BI_0 given by Gibson et al. (2009), which requires deep absorption features to produce a positive value of this index.

Table 1. Optical-to-near infrared Vega magnitudes of APM 08279+5255 in the observer frame available in the literature.

| Band | $\lambda_{eff}$ (Å) | $m_{ph}$ (mag) | $\Delta m_{ph}$ (mag) | Ref. |
|------|-----------------|---------------|-----------------|-----|
| B    | 4380            | 18.827        | 0.017           | 1   |
| V    | 5450            | 16.448        | 0.012           | 1   |
| R    | 6410            | 15.353        | 0.014           | 1   |
| I    | 7980            | 14.608        | 0.012           | 1   |
| J    | 12 200          | 13.340        | 0.030           | 2   |
| H    | 16 300          | 12.650        | 0.030           | 2   |
| K_γ | 21 300          | 12.080        | 0.030           | 2   |
| L’   | 34 500          | 9.900         | 0.040           | 2   |

References. (1) Ojha et al. (2009). (2) Egami et al. (2000).

The most common class of BAL QSOs ($\lambda$1400, C iv $\lambda$1549, Al iii $\lambda$1860, and Mg ii $\lambda$2800).

Table 2. APM 08279+5255 indexes of absorption associated to the main BAL transitions in quasars.

| Transition | BI (km s$^{-1}$) | BI_0 (km s$^{-1}$) | AI (km s$^{-1}$) |
|------------|-----------------|-------------------|-----------------|
| Si iv      | $<70$           | —                 | $<230$          |
| C iv       | 3370±200        | 2430±300          | 4210±240        |
| Al iii     | $<10$           | —                 | $<110$          |
| Mg ii      | $<170$          | —                 | $<490$          |

Notes. Locations marked with “—” indicate indexes for which a reliable upper limit cannot be provided.

Figure 2 shows the normalized spectral regions around Si iv, C iv, Al iii, and Mg ii. The values of BI, BI_0, and AI for each transition are listed in Table 2, along with the associated uncertainty. The most significant index of absorption detected at a confidence level $>3\sigma$. The only absorption feature that satisfies this criterion is the known BAL associated to C iv. However, when observed at high resolution, this absorption structure reveals to be not a single trough, but rather a complex system with two true C iv BALs at $v \sim -9750$ and $\sim -4500$ km s$^{-1}$ separated by narrow absorptions located around $v \sim -8500$ km s$^{-1}$ (Srianand & Petitjean 2000). Variability studies suggest that this narrow-absorption complex is nevertheless associated with C iv outflows, since it shows a variability pattern very similar to the C iv BAL (see e.g., Fig. 6 of Trevese et al. 2013). In this case the integral in Eq. (1) is calculated across the whole spectral range $\lambda$1400 – 1550, hence including all the features and giving values in agreement with those obtained by Trevese et al. (2013) for the equivalent width (EW) of the total absorption (from $\sim2300$ to $\sim4800$ km s$^{-1}$). In addition, the upper limits to the Si iv absorption strength reflect the sampling of the multiple narrow absorption identified by Ellison et al. (2004) as intervening C iv, Si iv, and Mg ii features (EW between $\sim90$ and $\sim140$ km s$^{-1}$; see their Table 2 and Fig. 2). With respect to the low-ionization transitions, the Al iii spectral region is affected by fringing in the 8300–9000 Å range that artificially increases the flux level with respect to the reference quasar template, thus preventing a reliable estimate of the Al iii absorption strength. The low-significance Mg ii feature, composed by two troughs respectively at $v \sim 0$ (not sampled by the BI) and $\sim -2 \times 10^3$ km s$^{-1}$, is between approximately ten and twenty times weaker than the C iv BAL when the Al ii or BI are used. Furthermore, any firm conclusion about the presence of Mg ii BALs is prevented by the low-sensitivity gap between the bands I and H. Therefore, we classify APM 08279+5255 as a high-ionization BAL QSO (HiBAL) due to the lack of unambiguous low-ionization absorption features.

The most common class of BAL QSOs (~85% of the BAL QSO population; e.g., Farrah et al. 2007) is that of the HiBALs. In particular, BALs associated with C iv represent the most common absorption troughs found in quasars, and are widely used to study the evolution of the BAL QSO population with cosmic time (Hewett & Foltz 2003; Reichard et al. 2003; Kigwe et al. 2008; Gibson et al. 2009; Allen et al. 2011) as well as to characterize the ensemble absorption variability timescales (Barlow 1993; Lundgren et al. 2007; Gibson et al. 2008, 2010; Capellupo et al. 2011, 2012, 2013; Filiz Ak et al. 2014). For instance, the time variability of the APM 08279+5255 C iv BAL has been studied in detail in Trevese et al. (2013) and Saturni et al. (2014, 2016), spanning a time interval of ~19 yr in the observer frame (i.e., ~3.9 yr in the restframe). The discovery of significant low-ionization troughs would have been extremely interesting to, for
Fig. 2. Flux of APM 08279+5255 normalized to the Vanden Berk et al. (2001) and Glikman et al. (2006) joint quasar template. The spectral regions around the Si IV emission (top left panel), the C IV emission (top right panel), the Al III emission (bottom left panel) and the Mg II emission (bottom right panel) are shown. In all panels, the velocity scale is relative to the systemic redshift $z = 3.911$ derived from the CO(4−3) and CO(9−8) emission lines (Downes et al. 1999). As a guidance, the zero-velocity position (dot-dashed line) and the normalized flux level (dashed line) are indicated.

example, unveil a possible transition between an obscured AGN phase and a normal quasar, as suggested by Farrah et al. (2007, 2012) for the case of ultraluminous IR galaxies (ULIRGs) such as APM 08279+5255 (Rowan-Robinson 2000). Nevertheless, the simultaneous presence of an UFO, a BAL and a molecular outflow in its spectrum makes APM 08279+5255 similar to the local quasar and ULIRG Mrk 231 (Feruglio et al. 2015), configuring this object as one of the best potential targets to investigate multi-phase outflows at higher redshifts and extreme energetic regimes (see e.g., Cicone et al. 2018).

3.2. Mg II, Hβ, and [O III] emission lines

In order to study the properties of the Mg II, Hβ, and [O III] emission lines of APM 08279+5255, we performed a spectral analysis of the two regions corresponding to the Hβ+[O III] (rest-frame wavelength range ∼3990–5040 Å, which also includes the Hγ λ4340 emission) and Mg II (restframe wavelength range ∼2200–3500 Å). The analysis was done by using custom IDL processing scripts, based on the IDL package MPFIT (Markwardt 2009). The emission lines and the continuum emission were fitted together, by minimizing the $\chi^2$. Figure 3 shows a magnification out of such spectral regions, which are characterized by strong Fe II emission producing a complex pseudo-continuum close to Hβ and Mg II.

As a first step, we tried to account for this Fe II-related emission in the restframe optical range by including the typical observational Fe II templates from Boroson & Green (1992), Véron-Cetty et al. (2004) and Tsuzuki et al. (2006) in the fits. We also considered the library of CLOUDY Fe II synthetic spectral templates presented in Bischetti et al. (2017) for hyper-luminous Type I quasars. In the fit, each template was convolved with a Gaussian whose width was free to vary, in order to account for the velocity dispersion of the gas. However, none of these templates was able to reproduce the Fe II spectral features observed in APM 08279+5255. Furthermore, we also found that the observational Fe II template from Vestergaard & Wilkes (2001) fails to reproduce the Fe II emission in the spectral region around Mg II. This failure might be partly due to the presence of telluric features in the near-IR spectra limiting the spectral windows used to anchor the fit. However, it is more likely that APM 08279+5255, being an exceptional object, shows an intrinsic difference in the Fe II emission properties, as the relative intensities of the main Fe II emission blends do not match any template from the adopted library. Furthermore, we also tried to simultaneously fit two different Fe II templates with independent velocity dispersion, as done in Vietri et al. (2018) in case of hyper-luminous quasars similar to APM 08279+5255 with strong Fe II emission. However, this did not result in an improvement. Therefore, we fitted the most prominent Fe II features in the spectrum by means of...
multiple Gaussian components. We tried to limit the dependence of the resulting line parameters on the adopted model by using a minimum number of Fe II components: in other words, we checked that adding another Gaussian component did not lead to a significant improve of the profile, with a FWHM free to vary in order to account for the Fe II emission redward the Hβ emission, while the second model (model B) accounts for the presence of both [O III] and Fe II in this spectral region. Specifically, model A includes a Gaussian component with FWHM free to vary in order to account for the Fe II emission at 4861 < λ < 5000 Å in the restframe; the upper bound was set taking into account the NICS spectral resolution of ~40 Å at these wavelengths in order to not overlap with spectral regions involving possible [O III] emission at 5007 Å.

Model B is similar to model A, but also includes two Gaussian components to fit the [O III] λλ4959,5007 Å doublet with a fixed FWHM = 1000 km s⁻¹, which is a typical upper limit to the width of emission lines associated to the narrow-line region. The centroids of the [O III] doublet components were fixed to 5007 Å and 4959 Å in the restframe, and the ratio of their normalizations was fixed at 1:3. Furthermore, both models include n total four Gaussian components to fit the Hβ and Hγ broad emissions, the strong Fe II emission features centered at ~4050 Å and ~4550 Å, and a power law to parameterize the continuum emission. Apart from the [O III] doublet, the velocity offset between all Gaussian components are free to vary. Both models are shown in Fig. 3b.

The restframe main spectral parameters, derived from the different models applied to the NICS data, are shown in Table 3. The Hβ emission is well reproduced by a broad Gaussian profile, with a FWHM~Hβ ~ 7000–7400 km s⁻¹, that appears to be slightly redshifted (ΔλHβ ~ 4868 Å, i.e., ~410 km s⁻¹) with respect to the systemic redshift z = 3.911 inferred from CO lines (Downes et al. 1999); however, given the dispersion error of ~8 Å in the restframe associated to the grism, the position of the Hβ emission peak is still consistent with the assumed systemic redshift. The addition of the [O III]-related components in model B yields a decrease of ∆χ² = 12 for one additional free parameter (i.e., the [O III] λ5007 Å normalization) compared to model A, which represents a statistical improvement at 98.7% confidence level according to an F-test. This suggests that a weak [O III] emission with F_{[OIII]}(5007 Å) = (1.8 ± 0.7) × 10⁻¹⁵ erg s⁻¹ cm⁻², corresponding to an [O III]-to-Hβ flux ratio F_{[OIII]}/F_{Hβ} = 0.04, can still be present in the optical spectrum of APM 08279+5255. Such an [O III] weakness is consistent with the detection of strong Fe II emission, according to Eigenvector 1 (e.g., Boroson & Green 1992; Shen & Ho 2014). However, we stress that any firm conclusion on the properties of [O III] emission in APM 08279+5255 is hampered by the low S/N and limited spectral coverage of the NICS data.

As for the fit to the spectral data in the Mg II emission region, we used a model consisting of one Gaussian component that accounts for the Mg II line, four Gaussian components to fit the main Fe II emission features centered respectively at ~2300 Å, ~2450 Å, ~2550 Å and ~3200 Å in the restframe, and a power law for the underlying continuum (see Fig. 3a). Such a fit yields a good description of the spectrum with an associated reduced χ² = 1.45. The best-fit value for the FWHM of the Mg II broad emission line is 9200±610 km s⁻¹. Remarkably, we found that the Mg II emission centroid is located at λ_{MgII} ~ 2789 Å blueshifted by 11 Å (1180 ± 430 km s⁻¹) with respect to the expected value at the systemic redshift. This blueshift is a factor of approximately two larger than the restframe dispersion error associated to the
Table 3. Spectral fit results derived for the Hβ+[O III] and Mg II regions of APM 08279+5255.

| Parameter                  | Hβ+[O III] region | Mg II region |
|----------------------------|-------------------|--------------|
| $\chi^2/\nu_{dof}$        | 3863/2012         | 3851/2011    |
| FWHM [km s$^{-1}$]        | 6990 ± 460        | 7360 ± 430   |
| $\beta_{MgII}$            | 4866 ± 7          | 4868 ± 7     |
| $\chi$ (5000 Å)           | 1.8 ± 0.7         | $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ |
| $\Delta L_a$(5100 Å)      | 5.1 ± 1.1         | 5.1 ± 1.2    | $10^{15}$ erg s$^{-1}$ |
| Mg II velocity shift      | ≤ 840 km s$^{-1}$ |              |

Fig. 4. Velocity shifts of the Hβ (blue), Mg II (red) and C IV (green) lines with respect to $z = 3.911$. The centroids of the best fit Gaussian profiles resulting from our analysis (Hβ and Mg II) and Saturni et al. (2016, C IV, based on high-resolution HST/STIS data) are indicated by vertical lines with the corresponding uncertainties (shaded vertical bands).

proxies of the BLR dynamics than C IV, whose profile is potentially affected by nonviral motion of the emitting gas (Baskin & Laor 2005; Shen & Liu 2012; Vietri et al. 2018). Furthermore, in the case of APM 08279+5255 the presence of strong BAL systems introduces additional uncertainty in the fit of the intrinsic C IV line profile. A direct measurement of $M_{BH}$ based on C IV and Si IV reverberation mapping (RM; e.g., Peterson 1997) was provided by Saturni et al. (2014), who analyzed the HST/STIS spectrum. They were, therefore, able to accurately recover the C IV emission profile without the contamination of telluric features associated to the Fraunhofer A band on the red wing of the line, deriving a FWHM of 7480 ± 70 km s$^{-1}$ and, in turn, a log $M_{BH}/L_\odot = 10.00_{-0.05}^{+0.07}$. The same RM-based value of $M_{BH}$ was also obtained for the Si IV line, strengthening an estimate that could be affected by nonviral components as in the case of C IV.

In our calculations, we have adopted the single-epoch relations derived by Bongiorno et al. (2014) for Mg II and Hβ, using the FWHMs and reddening-corrected monochromatic luminosities listed in Table 3. These relations can be expressed in the form:

$$\log \left( \frac{M_{BH}}{M_\odot} \right) = a + 0.5 \log \left( \frac{\Delta L_a(3000 \AA / 5100 \AA)}{10^{44} \text{ erg s}^{-1}} \right) + 2 \log \left( \frac{\text{FWHM}_\text{MgII}/H\beta}{1000 \text{ km s}^{-1}} \right),$$

with the parameter $a = 6.6$ for Mg II and 6.7 for Hβ respectively. In addition to the estimates of $M_{BH}$ based on the Hβ and Mg II from the TNG spectrum, we also derive an additional

4. Single-epoch black hole mass estimates

The TNG observations of APM 08279+5255 allow us to provide the virial single-epoch black hole mass $M_{BH}$ using Mg II and Hβ emission lines. These lines are much more reliable

grism resolution in this spectral range, and is also approximately two times smaller than the blueshift of 2500 ± 40 km s$^{-1}$ measured for the C IV emission (and valid for other high-ionization emission lines such as N v, Si iv and C iii); e.g., Irwin et al. 1998) from the R-band spectrum taken with the high-resolution spectrograph STIS on board of HST (Lewis et al. 2002b). We show this blueshift dependence on wavelength in Fig. 4, where the centroid shifts measured for C IV, Mg II, and Hβ broad emission lines are compared. This figure highlights that the Mg II emission line can be affected by a strong blueshift in the same way as high-ionization features. This can therefore bias the single-epoch SMBH mass estimate based on this low-ionization transition in case of highly-accreting AGN (e.g., Marziani et al. 2013). In particular, Mg II is extensively used to measure the SMBH mass of high-luminosity quasars at $z > 5$, due to the fact that Hβ line is no longer observable in the K band.

Previous studies found the [O III] weakness to be associated with broad blueshifted C IV emission in samples of Type 1 luminous quasars (e.g., Netzer et al. 2004). In their study of the optical-to-UV spectra of WISE/SDSS selected hyper-luminous quasars (WISEH; e.g., Bischetti et al. 2017), Vietri et al. (2018) have indeed found that ~70% of them exhibit very weak [O III] emission (<5 Å) and largely blueshifted (~2000–8000 km s$^{-1}$) C IV emission with restframe EWs ≤ 20 Å. They interpreted these properties in terms of a steep UV-to-X-ray continuum in luminous quasars coupled to a face-on view of the continuum source. The former property leads to an efficient line-driving acceleration mechanism for broad-line region (BLR) winds (Proga & Kallman 2004; Wu et al. 2009; Risaliti & Elvis 2010; Richards et al. 2011), while the latter implies an observed small EW of the [O III] emission line (see Bisogni et al. 2017). The reconstruction of the C IV line profile on the APM 08279+5255 HST/STIS spectrum made by Saturni et al. (2016) allows us to compute a C IV restframe EW of 24 ± 2 Å. This value is in agreement with the C IV EWs commonly measured in other very luminous quasars with weak [O III] and large C IV blueshift.
Table 4. SMBH mass and Eddington ratio of APM 08279+5255 derived from Hβ, Mg ii and C iv broad emission lines, as a function of the magnification parameter $\mu$.

| Transition | $\mu = 1$ | $\mu = 4$ | $\mu = 100$ |
|------------|-----------|-----------|-------------|
| Hβ        | 10.29 ± 0.32 | 9.99 ± 0.32 | 9.29 ± 0.32 |
| Mg ii     | 10.45 ± 0.34 | 10.14 ± 0.34 | 9.45 ± 0.34 |
| C iv      | 10.54 ± 0.31 | 10.22 ± 0.31 | 9.48 ± 0.31 |

$\lambda_{\text{Edd}}$ in $\mu$ intervals.

| Transition | $\mu = 1$ | $\mu = 4$ | $\mu = 100$ |
|------------|-----------|-----------|-------------|
| Hβ        | 1.1 ± 0.8 | 0.5 ± 0.4 | 0.11 ± 0.08 |
| Mg ii     | 0.8 ± 0.6 | 0.4 ± 0.3 | 0.08 ± 0.05 |
| C iv      | 0.7 ± 0.4 | 0.4 ± 0.2 | 0.08 ± 0.05 |

We derive such a luminosity from the lensed monochromatic luminosity at 3000 Å adopting the bolometric correction with nonzero intercept by Runnoe et al. (2012a,b):

$$L_{\text{bol}} = 0.75 \left[10^{1.852} \cdot \lambda L_\lambda(3000 \text{ Å}^{0.975})\right]$$

We consider this estimate of $L_{\text{bol}}$ as our fiducial value instead of deriving such a quantity from the fit of APM 08279+5255 spectral energy distribution (SED), since we note that the SED itself is affected by a wavelength-dependent magnification factor resulting from the contribution of emitting regions of different size. In this way, we are also consistent with the UV-to-optical luminosities used to evaluate the single-epoch SMBH mass of APM 08279+5255.

Dong et al. (2009) reported the existence of a strong correlation between the EW of Mg ii and $\lambda_{\text{Edd}}$, i.e., $EW_{\text{Mg} \text{ ii}} \propto \lambda_{\text{Edd}}^{0.4}$. Such an effect is possibly due to a decrease in the covering factor of the Mg ii BLR at increasing $\lambda_{\text{Edd}}$ (i.e., the number of Mg ii emitting clouds decreases due to radiation-pressure blowing; see also Fabian et al. 2006; Marconi et al. 2008, 2009). We used this relation to obtain an independent estimate of $\lambda_{\text{Edd}}$ for APM 08279+5255. The restframe EW derived from the TNG spectrum is $EW_{\text{Mg} \text{ ii}} = 27.1 \pm 1.5$ Å, which corresponds to $\lambda_{\text{Edd}} = 0.36^{+0.51}_{-0.21}$ taking into account the scatter of 0.38 dex in $\lambda_{\text{Edd}}$ in the Dong et al. (2009) data. We note that the confidence interval of $\lambda_{\text{Edd}}$ obtained in this way is fully consistent with the values listed in Table 4 for the case of $\mu = 4$, and only marginally consistent for the case of $\mu = 100$. This suggests that a moderate lens magnification $\mu < 100$ for APM 08279+5255 can be favored over a more extreme value.

We can then derive an independent estimate of $\mu$ using the $\lambda_{\text{Edd}}$ obtained from the Dong et al. (2009) relation. In fact, from Eq. (3) we derive that $\lambda_{\text{Edd}} \propto \mu^{1-b}$, and hence

$$\mu = \frac{\lambda_{\text{Edd}}^{\text{(obs)}}}{\lambda_{\text{Edd}}^{\text{(true)}}}^{b},$$

with $b = 0.4$ and $\beta \approx 0.6$.

Table 4 shows the estimates of the $M_{\text{BH}}$ of APM 08279+5255 based on the different transitions. Due to the fact that APM 08279+5255 is lensed by a foreground system which remains unobserved, at least two competing lens models have been proposed to explain the lack of a lens image. Egami et al. (2000) proposed a naked-cusp configuration in which the magnification at UV-to-optical wavelengths can rise up to $\sim 100$. Richers et al. (2009) derived their lens model from the analysis of the CO emission region, finding a lower, almost achromatic magnification of approximately four. Accordingly, Table 4 lists the SMBH mass estimates as a function of different values of the magnification parameter: $\mu = 1$ (i.e., no magnification), 4 and 100 respectively. The error associated to $M_{\text{BH}}$ includes in quadrature both the statistical uncertainties and intrinsic scatter in the single-epoch relations of $-0.26$ dex (Vestergaard & Peterson 2006; Shen et al. 2011; Borgiorno et al. 2014). Even in the most conservative case of $\mu = 100$, the $M_{\text{BH}}$ derived by considering the Hβ emission line is $>0.9 M_{\odot}$, which indicates that APM 08279+5255 harbors a SMBH at the highest end of the $M_{\text{BH}}$ distribution.

In Table 4 we also report the estimate of the Eddington ratios $\lambda_{\text{Edd}} = L_{\text{bol}}/L_{\text{bol}}$ based on these $M_{\text{BH}}$ values, assuming a bolometric luminosity $L_{\text{bol}} = 2.7 \times 10^{47}$ erg s$^{-1}$ before correcting for $\mu = 4$ and 100 (which correspond to a true bolometric luminosity of $6.8 \times 10^{47}$ erg s$^{-1}$ and $2.7 \times 10^{46}$ erg s$^{-1}$ respectively).

5. Summary and conclusions

In this work, we have presented the quasi-simultaneous UV-to-optical spectrum of APM 08279+5255 taken at TNG with the instruments DOLORes and NICS. The presence of a UFO, a BAL and a molecular outflow in this object is of great interest to explore the properties of multiphase quasar winds at high redshifts and extreme luminosities with dedicated multiwavelength observations, in order to probe the possible presence of...
ongoing AGN feedback. This spectrum covers the previously unobserved region between C IV and [O III], thus providing important constraints on the BAL classification, the SMBH mass, the Eddington ratio and the magnification factor in this high-$z$ quasar. Our main results can be summarized as follows:

- We tested the balnicity of APM 08279+5255 for high- and low-ionization transitions. We computed the most commonly used indexes (B1, B2, and A1) of absorption for Si iv, C iv, Al iii, and Mg ii, confirming the BAL only for C iv and hence supporting a HiBAL rather than a LoBAL classification for APM 08279+5255.

- The near-infrared NICS spectrum has allowed us, for the first time, to study the spectral regions corresponding to the Hβ+[O III] and Mg ii emission lines in APM 08279+5255. The Hβ line profile shows a FWHM of ~7400 km s$^{-1}$ and a centroid consistent with the CO-based systemic redshift $z = 3.911$. Conversely, the Mg ii emission line (FWHM ~ 9200 km s$^{-1}$) is characterized by a blueshift of ~1200 km s$^{-1}$, lower by a factor of approximately two than the blueshift of ~2500 km s$^{-1}$ measured for the C iv emission line. This result is in agreement with previous works that find larger blueshifts in high-ionization transitions (Richards et al. 2002; Baskin & Laor 2005).

- We also investigated the presence of [O III] λλ4959,5007 Å emission in a spectral region very close to the red edge of the NICS spectrum and characterized by strong Fe ii emission. Our best-fit model includes a low-significance [O iii] component with $F_{\text{OIII}}(5007) \sim 1.8 \pm 0.7 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$. This indicates that the [O iii] emission in APM 08279+5255 is intrinsically weak with $F_{\text{OIII}}/F_{\text{HÎ}} = 0.04$, consistent with the prediction of Eigenvector 1 (Boroson & Green 1992) of an anti-correlation between Fe ii and [O iii] emission. APM 08279+5255 therefore shares the properties of the [O iii] and C iv emission lines observed in other sources lying at the bright end of the AGN luminosity function (Richards et al. 2011; Shen & Ho 2014; Zuo et al. 2015; Marziani et al. 2016; Shen 2016; Vietri et al. 2018).

- We have been able to derive for the first time estimates of the $M_{\text{BH}}$ in APM 08279+5255 based on the Hβ and Mg ii emission lines. These transitions have been found to provide a much more reliable measurement of $M_{\text{BH}}$ in AGN than C iv. This is even more true in the case of APM 08279+5255, whose C iv emission line is affected by BAL features. We find very large mass values ($\log M_{\text{BH}}/M_\odot \gtrsim 9.3$) for a magnification factor $\mu$ varying from 1 (i.e., no magnification) to 100 (Egami et al. 2000). A value of $\mu = 4$ (Riechers et al. 2009) is compatible with the RM-based $M_{\text{BH}}$ estimate of $\log M_{\text{BH}}/M_\odot \sim 10$ given in Saturni et al. (2016). The EW$_{\text{HÎ}}$-based estimate of $\Delta E_{\text{LAD}}$ according to the EW $- \Delta E_{\text{LAD}}$ relation by Dong et al. (2009) also suggests a moderate magnification factor $4.1 \leq \mu \leq 9.3$, corresponding to an intrinsic bolometric luminosity $2.9 \times 10^{47} \leq L_{\text{bol}} \leq 6.7 \times 10^{47}$ erg s$^{-1}$ and a black hole mass $6.5 \times 10^{9} \leq M_{\text{BH}} \leq 1.5 \times 10^{10} M_\odot$. This is in turn compatible with the upper limit $\mu \lesssim 8.2$ found by Saturni et al. (2016) with RM, and the limit $\mu \lesssim 50$ derived from the single-epoch relations by adopting the minimal black hole mass $M_{\text{BH}} = 4 \times 10^{9} M_\odot$ inferred by Hagino et al. (2017) through APM 08279+5255 SED modeling.

Being taken 76 days apart (corresponding to only ~15 restframe days), the UV and optical spectral sections of APM 08279+5255 probe the same AGN state. This allowed us to study its physical properties consistently during a state of relatively constant AGN emission. Indeed, this source has been found to vary in continuum, emission- and absorption-line intensity, with flux changes of up to ~0.5 mag (Trevese et al. 2013; Saturni et al. 2016). Therefore, multiband spectroscopic observations of APM 08279+5255 must be quasi-simultaneous in order to overcome the lack of a common reference for a compatible flux calibration between spectra taken at different epochs. The possibility to observe APM 08279+5255 with the forthcoming James Webb Space Telescope (JWST) is hence of extreme interest, since the spectro-photometric capabilities of its instruments, simultaneously covering the wavelength range $\lambda\ell 6000 - 2.8 \times 10^{4} \AA$ (Dorner et al. 2016; Labiano et al. 2016), may allow for this source the detailed study of the stratified BLR dynamics around its central black hole and the characterization of the outflows associated to emission features from Si iv to molecular lines.

Finally, we note that the estimates of $\mu$ and $\Delta E_{\text{LAD}}$ presented in this work are based on the comparison of the SE measurements of $M_{\text{BH}}$ with the direct SMBH mass measurement by Saturni et al. (2016), which relies, in turn, on the reverberation mapping of the high-ionization C iv and Si iv lines that are affected by narrow (intrinsic or intervening) and broad absorption. Such absorption may bias the determination of $M_{\text{BH}}$, and this bias is difficult to quantify. Future observations aimed at directly measuring APM 08279+5255 $M_{\text{BH}}$ with novel techniques, such as BLR spectroastrometry, are therefore needed. In particular, the spectroastrometric technique presented in Stern et al. (2015) may potentially allow to spatially resolve the kinematics of broad-line regions with single spectroscopic observations taken at high signal-to-noise ratio ($S/N \gtrsim 40$) in adaptive optics (AO) regime. Such capabilities are already at reach of current-generation telescopes such as the Large Binocular Telescope (LBT). Therefore, the AO infrared spectroscopy of APM 08279+5255 is a primary task to place better constraints on its SMBH mass and thus to obtain a more robust evaluation of lens magnification and accretion properties.

Acknowledgements. We thank our anonymous referee for their helpful comments. We acknowledge R. Maiolino (Kavli Institute for Cosmology) and D. Trevese (“Sapienza” University of Rome) for useful discussions. This research is based on observations made with the Italian Telescopio Nazionale Galileo (TNG) operated on the island of La Palma by the Fundación Galileo Galilei of the INAF (Istituto Nazionale di Astrofisica) at the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of the Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation. CC and CF acknowledge funding from the European Union’s Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie grant agreement No. 664931. GV acknowledges funding support from the DFG Cluster of Excellence “Origin and Structure of the Universe” (www.universe-cluster.de).

References

Allen, J. T., Hewett, P. C., Maddox, N., Richards, G. T., & Belokurov, V. 2011, MNRAS, 410, 860
Barlow, T. A. 1993, PhD Thesis, California University, USA
Baskin, A., & Laor, A. 2005, MNRAS, 356, 1029
Bisochi, M., Piconcelli, E., Vietri, G., et al. 2017, A&A, 598, A122
Bisogni, S., Marconi, A., & Risaliti, G. 2017, MNRAS, 464, 385
Bongiorno, A., Maiolino, R., Brusa, M., et al. 2014, MNRAS, 443, 2077
Boroson, T. A., & Green, R. F. 1992, ApJS, 80, 109
Capellupo, D. M., Hamann, F., Shields, J. C., Rodríguez Hidalgo, P., & Barlow, T. A. 2011, MNRAS, 413, 908
Capellupo, D. M., Hamann, F., Shields, J. C., Rodríguez Hidalgo, P., & Barlow, T. A. 2012, MNRAS, 422, 3249
Capellupo, D. M., Hamann, F., Shields, J. C., Halpern, J. P., & Barlow, T. A. 2013, MNRAS, 429, 1872
Chartas, G., Brandt, W. N., Gallagher, S. C., & Garnire, G. P. 2002, ApJ, 579, 169
Cicone, C., Brusa, M., Ramos Almeida, C., et al. 2018, Nat. Astron., 2, 176
