

# **Gaia-assisted discovery of a detached low-ionisation BAL quasar with very large ejection velocities**

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## **ABSTRACT**

We report on the discovery of a peculiar broad absorption line (BAL) quasar identified in our *Gaia*-assisted survey of red quasars. The systemic redshift of this quasar was difficult to establish because of the absence of conspicuous emission lines. Based on deep and broad BAL troughs of at least Si IV, C IV, and Al III, a redshift of  $z = 2.41$  was established under the assumption that the systemic redshift can be inferred from the red edge of the BAL troughs. However, we observe a weak and spatially extended emission line at 4450 Å that is most likely due to Lyman- $\alpha$  emission, which implies a systemic redshift of  $z = 2.66$  if correctly identified. There is also evidence for the onset of Lyman- $\alpha$  forest absorption bluewards of 4450 Å and evidence for H $\alpha$  emission in the *K* band consistent with a systemic redshift of  $z = 2.66$ . If this redshift is correct, the quasar is an extreme example of a detached low-ionisation BAL quasar. The BALs must originate from material moving with very large velocities ranging from 22 000 km s<sup>-1</sup> to 40 000 km s<sup>-1</sup>. To our knowledge, this is the first case of a systemic-redshift measurement based on extended Lyman- $\alpha$  emission for a BAL quasar. This method could also be useful in cases of sufficiently distant BL Lac quasars without systemic-redshift information.

**Key words.** quasars: general – quasars: absorption lines – quasars: individual: GQ 1309+2604

## **1. Introduction**

The formation and growth of super-massive black holes in the centres of galaxies is a key element in the entire cosmic history of structure formation. Understanding how super-massive black holes form also informs us about baryonic processes in galaxy formation, for example how gas is accreted. The feedback processes from accreting super-massive black holes, in the form of active galactic nuclei or quasars, is a key element in regulating star formation (see Peterson 2008; Fabian 2012; Netzer 2015; Hickox & Alexander 2018, for recent reviews). The phenomenon of powerful outflows from quasars, in which material is seen being ejected from the central engine with very large velocities of 0.1–0.2 *c*, is more directly related to the object presented in this paper (see King & Pounds 2015, for a review).

The spectral energy distributions of a large fraction of active galactic nuclei are remarkably similar and are characterised by a very broad energy output extending over more decades in frequency space than for sources powered by nuclear fusion. This broad spectral energy output forms the basis for a wide range of selection methods for quasars, for example X-rays, ultraviolet excess, millimetre emission, and radio emission (see e.g.

Richards et al. 2006; Heintz et al. 2016, and references therein). Photometric variability is also an important selection method for active galactic nuclei (e.g., Ulrich et al. 1997; Schmidt et al. 2010).

The object discussed in this short paper was discovered in a wider survey for quasars. One of the main goals of this survey is to construct a more complete and (in terms of colour) more unbiased sample of quasars, partly based on astrometric data. Specifically, the second *Gaia* data release (*Gaia*-DR2; Gaia Collaboration 2018) is used to select point sources that are stationary, which indicates that they may be extragalactic (Heintz et al. 2015, 2018). This approach strongly reduces the contamination from stars during follow-up spectroscopy.

Heintz et al. (2018, see also Krogager et al. 2016) have in this manner built a catalogue of candidate quasars using a combination of astrometry from *Gaia*-DR2 and photometry from the optical Sloan Digital Sky Survey data release 12 (SDSS-DR12, Eisenstein et al. 2011), the near-infrared UKIRT Infrared Deep Sky Survey (UKIDSS, Warren et al. 2007), and the mid-infrared all-sky Wide-field Infrared Survey Explorer mission (WISE, Cutri et al. 2013). The object examined in this paper, designated GQ 1309+2904 with equatorial coordinates of the target

RA = 13:09:23.91, Dec = +29:04:51.7 (J 2000.0), was observed as part of a larger spectroscopic campaign of candidate quasars from this survey. We present spectroscopic observations of the broad absorption line (BAL) quasar GQ 1309+2904, and discuss its systemic redshift and the implied properties of the BALs.

## 2. Observations and data reduction

The first spectroscopic observations of this candidate quasar were obtained with the OSIRIS instrument at the Gran Telescopio Canarias (GTC). The candidate quasar was observed on January 5, 2019, at which time three 500 s integrations were obtained. We used Grism R1000B and a 1.0 arcsec slit, providing a full width at half maximum (FWHM) resolution of  $\mathcal{R} = 600$  and a spectral range from 3750 Å to 7800 Å. Conditions were good with a seeing of about 0.9 arcsec. We observed the target at low air mass, ranging from 1.02 to 1.04. We secured additional spectroscopy ( $4 \times 800$  s) through a fast-track programme at the Nordic Optical Telescope (NOT) on April 29, using the low-resolution spectrograph AIFOSC and Grism 20, covering the spectral range from 6000 Å to 10 100 Å with a 1.0 arcsec wide slit providing a resolution of  $\mathcal{R} \approx 770$ . Conditions were again good with a seeing of about 1.0 arcsec and low air mass (below 1.03). We subsequently observed the target in the near-infrared, first with MOSFIRE at the Keck telescope in the *J* band on June 5, 2019 for 1440 s under  $\sim 0.6$  arcsec seeing. We employed a 3-slitlet longslit set-up, resulting in a 21.6 arcsec long, 0.7 arcsec wide aperture with an ABAB dither pattern and, as recommended by the MOSFIRE team, 120 s individual exposures. Finally, on June 12, 2019, we observed the target with LIRIS mounted on the *William Herschel* Telescope (WHT). We used the low-resolution HK grism and a 1.0 arcsec slit, covering the *H* and *K* bands at a resolution of 700. We obtained 15 exposures in ABAB sequences with a total integration time of 3600 s. These observations were obtained under good conditions with a seeing below 1 arcsec and at low air mass (1.2).

The spectroscopic data from the GTC, NOT, and WHT were reduced using standard procedures in IRAF<sup>1</sup>. The spectra were flux calibrated using observations of the spectro-photometric standard stars Feige 110 and BD +26 2606 observed on the same nights. The MOSFIRE spectra were reduced using dedicated software.

We did not have a flux standard observation for the LIRIS data. Instead, we observed the telluric A0V standard HIP 68209. We used the spectrum of Vega to derive a relative sensitivity function and then scaled the fluxed spectra to the photometry in the *H* and *K* bands.

## 3. Results

### 3.1. Line identification

In Fig. 1 our spectra of GQ 1309+2904 are shown together with photometry from SDSS, UKIDSS, and WISE. The GTC spectrum shows a red shape and the presence of very broad and deep absorption features; the three clearest are centred at around 6180 Å, 5150 Å, and 4640 Å. It is obvious that the object is not a star. The source is also detected in all four WISE bands

with colours consistent with the colours of quasars (Table 1, the *W1* – *W2* colour was part of the selection criteria). The source is not detected in the FIRST survey at radio frequencies (Becker et al. 1995), which is consistent with the properties of most BAL quasars (Morabito et al. 2019).

The spectrum looks very different from normal type I quasars because of the absence of broad emission lines. It also looks different from typical BAL quasars in that the BALs are broader and with much less pronounced P-Cygni profiles than normally seen for BAL quasars (e.g. Hall et al. 2002; Gibson et al. 2009). As an example, the BAL line at 5150 Å has an observed equivalent width of more than 200 Å.

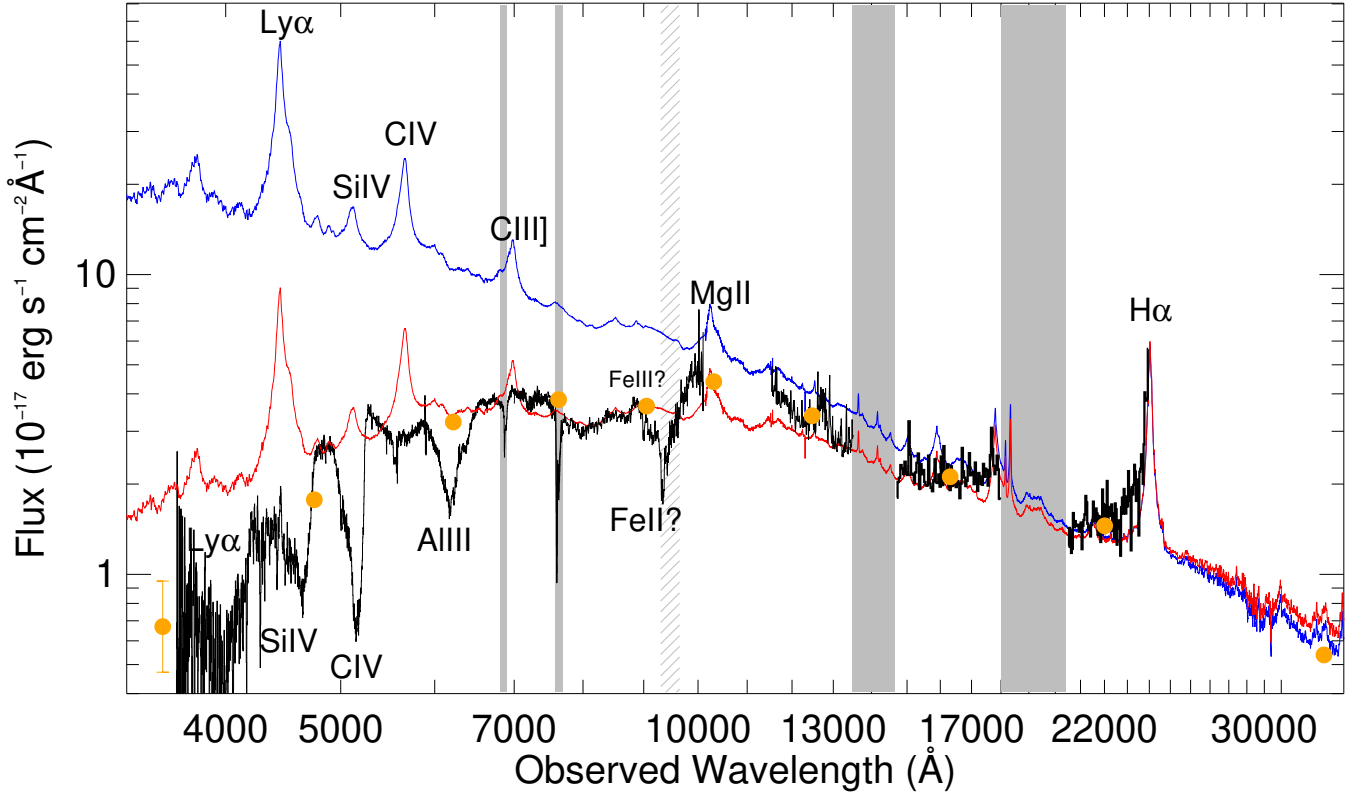
We first suspected that the three main troughs in the GTC spectrum of GQ 1309+2904 were due to Si IV, C IV, and Al III, at a redshift of roughly  $z = 2.41$ , based on the red-most edges of the troughs. This would make GQ 1309+2904 a low-ionisation BAL quasar (Voit et al. 1993). However, upon closer inspection of the trace we identified a spatially extended emission line at 4450 Å (see Figs. 2 and 3). The line is spatially asymmetric, extending more than 2 arcsec to one side of the trace and slightly less on the other side. This extended feature is present in all three individual GTC spectra and is hence not caused by a cosmic ray hitting close to the trace. To better show this extended component, we have applied spectral point spread function (SPSF) subtraction following the procedure described in Møller (2000). We have conservatively scaled the SPSF such that the flux is zero at the centre of the trace. As seen in Fig. 3, there is spatially extended emission on either side of the trace. The velocity width of the line is about  $1200 \text{ km s}^{-1}$ . It is natural to interpret this line as Lyman- $\alpha$ , as extended Lyman- $\alpha$  emission is very commonly detected from luminous quasars, including BAL quasars (e.g. Heckman et al. 1991; Fynbo et al. 1999; Møller et al. 2000; Weidinger et al. 2005; Christensen et al. 2006; Ginolfi et al. 2018; Cai et al. 2019). The flux of the line is also in the range of those measured for extended Lyman- $\alpha$  emission around quasars at similar redshifts (Cai et al. 2019). This interpretation implies a significantly higher redshift of  $z = 2.66 \pm 0.01$ .

### 3.2. NOT spectrum

A systemic redshift of  $z = 2.66$  could explain the apparent flux-drop in the *z* band compared to the *Y* band, which at this redshift would be due to a Mg II emission line in the *Y*-filter, and the possible BAL absorption due to Fe II in the *z*-band. The objective of the NOT spectrum was to check for this possibility. In the NOT spectrum, there is indeed an additional deep absorption trough centred at around 9340 Å. Therefore the spectrum seems to be consistent with such an interpretation (compare e.g. spectra of H 1011+091 in Hartig & Baldwin 1986, HAQ 1114+1330 in Krogager et al. 2015, or eHAQ 1514–0002 in Krogager et al. 2016). The NOT spectrum is rising towards the red extreme, which is consistent with a strong Mg II emission line in the *Y*-filter.

In the NOT spectrum, there is also evidence for an emission line consistent with Fe III  $\lambda 2418$  (also called Fe III UV47) at  $z = 2.66$ , although it is difficult to infer with certainty if this feature is an emission line or a transmission peak between BAL troughs. The Fe III UV47 emission line has previously been seen in BAL quasars (Laor et al. 1997; Vestergaard & Wilkes 2001). On the red wing of the telluric A absorption band, there is evidence for emission centred around 6980 Å, which is consistent with a weak C III] and/or Fe III UV34 at  $z \approx 2.66$  (see Vestergaard & Wilkes 2001, their Fig. 5).

<sup>1</sup> IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.



**Fig. 1.** Spectra of GQ 1309+2904 from GTC, NOT, MOSFIRE, and LIRIS are shown together with *ugriz*, *YJHK*, and W1 photometry from the SDSS, UKIDSS, and WISE surveys (orange points). The spectra are shown with logarithmic axes to better point out all important details. The shaded areas around 6800 Å and 7600 Å indicate the locations of the telluric A and B absorption bands. A region with many narrow telluric lines at 9300–9650 Å is indicated by shading, which may affect the appearance of, but cannot fully account for, the BALs seen there. The MOSFIRE spectrum is interpolated across skyline residuals for illustration purposes. Except for the *u* band (where the error is 0.38 mag), the error bars on the photometric data points are smaller than the plotting symbols. Also overplotted are a template quasar spectrum from Selsing et al. (2016) redshifted to  $z = 2.66$  (in blue) and this same spectrum reddened by SMC-like extinction with  $A_B = 0.55$  mag (in red).

**Table 1.** Optical and near-infrared magnitudes from SDSS (AB magnitudes from Alam et al. 2015), UKIDSS (Vega magnitudes from Warren et al. 2007), and WISE (Vega magnitudes from Cutri et al. 2013).

<i>u</i>	<i>g</i>	<i>r</i>	<i>i</i>	<i>z</i>	<i>Y</i>	<i>J</i>	<i>H</i>	<i>K</i>	W1	W2	W3	W4
22.84	21.13	19.88	19.25	18.92	17.80	17.39	16.83	16.13	15.43	14.51	10.95	8.52

### 3.3. Near-infrared spectra

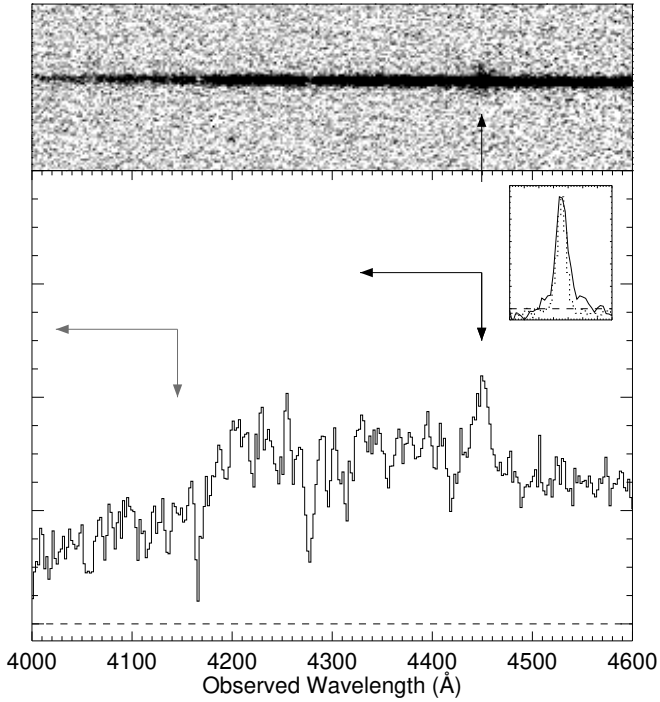
The MOSFIRE spectrum covering the *J* band shows a flat continuum with a slope that is consistent with the photometry. There is a possible emission feature around 12 600 Å, which we have not been able to identify. The LIRIS spectrum shows a flat spectrum in the *H* band. In the *K* band, the flux is rising towards the red which is consistent with a strong H $\alpha$  emission line at  $z = 2.66$ . We can rule out the presence of a strong H $\alpha$  emission line at  $z = 2.41$ .

### 3.4. Lyman- $\alpha$ forest

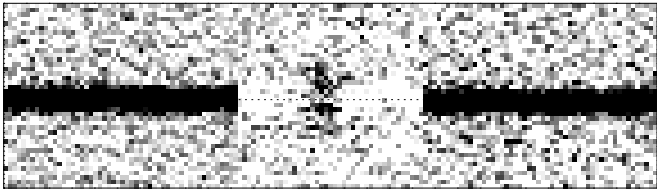
Consistent with the inferred redshift of  $z = 2.66$ , we also observe evidence for the onset of the Lyman- $\alpha$  forest shortwards of 4450 Å. If the redshift were  $z = 2.41$ , the Lyman- $\alpha$  forest would begin at around 4145 Å, but we do detect narrow absorption lines in the wavelength range 4145–4450 Å (see Fig. 2). No similarly narrow absorption lines are detected redwards of 4450 Å.

### 3.5. Velocity structure of the BAL lines

In Fig. 4, we plot the three main broad absorption troughs and Lyman- $\alpha$  under the assumption that the systemic redshift is  $z = 2.66$  and that the broad lines are due to Si IV, C IV, and Al III. The velocities are calculated using Eq. (1) in Foltz et al. (1986). The inferred blue-shifts are extremely large extending up to terminal blue-shift velocities of about  $-40\,000$  km s $^{-1}$ . The C IV trough has a very well-defined red edge starting at a blue-shift of about  $-22\,000$  km s $^{-1}$ . If we are correct about the inferred systemic redshift of  $z = 2.66$ , GQ 1309+2904 is hence an extreme example of a detached BAL quasar. For comparison, there are only two to three detached BAL quasars with minimum ejection velocities above  $20\,000$  km s $^{-1}$  in the sample of more than 72 BALs studied by Lee & Turnshek (1995). Benn et al. (2005) also reported a quasar with a C IV BAL detached by more than  $20\,000$  km s $^{-1}$ . In the spectrum of GQ 1309+2904 there is also evidence for a weaker BAL component at a smaller velocity of about  $6\,000$  km s $^{-1}$  seen both in C IV and Si IV.



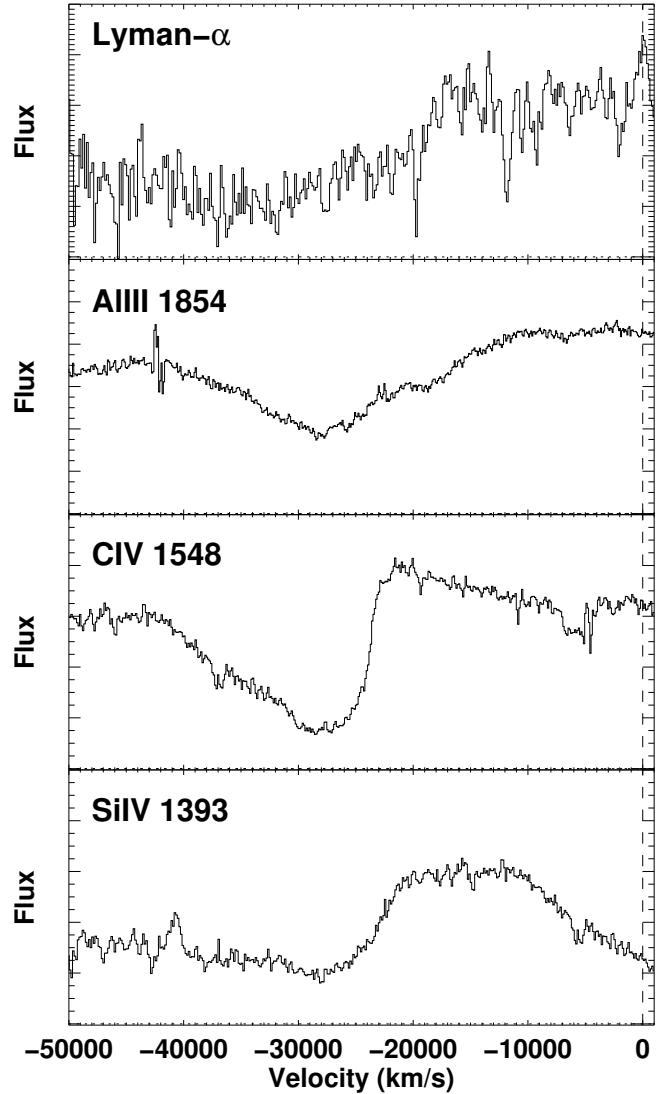
**Fig. 2.** Zoom-in on blue part of the spectrum both in the 2D spectrum (*top panel*) and 1D spectrum (*bottom panel*). The black arrows indicate the location of the spatially extended emission line, which we interpret as Lyman- $\alpha$  emission with a FWHM of  $\approx 1200 \text{ km s}^{-1}$ , and the start of the Lyman- $\alpha$  forest at  $z = 2.66$ . There are several narrow absorption lines shortwards of the alleged Lyman- $\alpha$  line, which would be consistent with the onset of the Lyman- $\alpha$  forest. If the redshift was  $z = 2.41$ , then the Lyman- $\alpha$  forest would only begin around  $4145 \text{ \AA}$  (denoted with dark grey arrows). The insert shows the spatial profile averaged over the wavelength range  $4447\text{--}4455 \text{ \AA}$  (solid line, covering the spatially extended emission line, which we interpret as Lyman- $\alpha$ ) compared to the continuum profile averaged over the wavelength range  $4500\text{--}4600 \text{ \AA}$ .



**Fig. 3.** Image of spectral PSF subtraction to remove the light from the central unresolved emission component at  $4450 \text{ \AA}$ . The maximal point source contribution is subtracted to create a hole in the middle of the spatial profile of the emission line. Even after this conservative procedure, a clear, extended component on either side of the quasar trace is denoted with a dotted line. These properties make the interpretation of this line as Lyman- $\alpha$  most likely compared to alternative explanations involving the superposition of two unrelated objects on the slit.

### 3.6. Photometric variability

The strength of the lines and the very high blue-shifts suggest that this source is likely to be variable (Lundgren et al. 2007). The Pan-STARRS data release 2 catalogue contains data of the quasar field in the *grizy* filters, obtained over a time span of two to three years with 6–12 measurement points per filter. We extracted all photometric data and corrected for atmospheric extinction. Computing the mean fractional flux variation of the object following the definitions described in Peterson



**Fig. 4.** Broad absorption lines plotted in velocity space shortwards of the proposed systemic redshift of  $z = 2.66$ . The three doublets are shown as the bluest components of the doublets, i.e.  $1393 \text{ \AA}$ ,  $1548 \text{ \AA}$ , and  $1854 \text{ \AA}$ , for Si IV, C IV, and Al III, respectively.

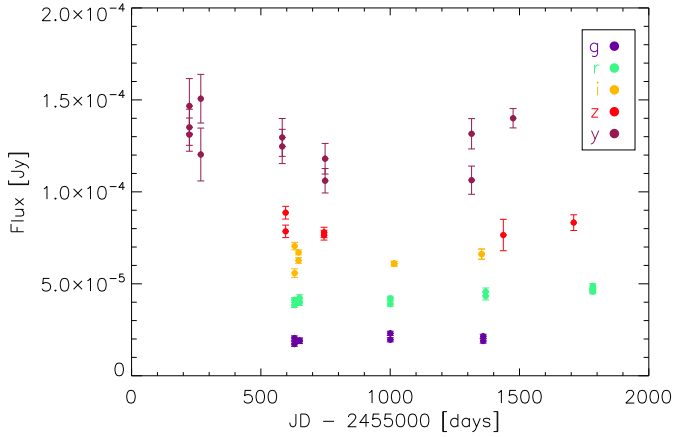
(2001), which takes into account individual flux measurement uncertainties, we determine that in each filter the variability is 5–7%, which is within the range of normal variability for quasars, including BAL quasars (Vanden Berk et al. 2004). Figure 5 shows light curves from the five filters.

### 3.7. Possibility of multiple sources on the slit

A possible, although unlikely, interpretation of our data is that there could be two sources at different redshifts superposed on the slit: an extended Lyman- $\alpha$  emitter at  $z = 2.66$  and a foreground BAL quasar at  $z = 2.41$ . We checked the existing imaging from SDSS, UKIDSS, and Pan-STARRS to search for any evidence for multiple sources along the line of sight. However, in all bands the source is consistent with being a single point source and any additional source would have to be at least ten times fainter than the main component (this of course depends somewhat on the impact parameter).

Another possibility could be that the emission line at  $4450 \text{ \AA}$  is due to an emission line other than Lyman- $\alpha$ . Two arguments





**Fig. 5.** Light curves of GQ 1309+2904 from Pan-STARRS DR2 catalogue data in the *grizy* filters demonstrate mean fractional variations of 5–7% over the course of 2–3 years.

render this possibility unlikely. First, there is no evidence for other narrow emission lines next to the trace of any of our spectra, which we would expect if the line were for example due to [O II]. Second, the velocity width of the line is too large for such an interpretation. Very broad lines would belong to massive galaxies that should be detectable in existing imaging data.

#### 4. Discussion and conclusions

Normally, it is not difficult to estimate the systemic redshift of quasars to within at least one percent, but the spectrum of GQ 1309+2904 is very unusual compared to hundreds of BAL quasars we have observed in our surveys. GQ 1309+2904 is a low-ionisation BAL quasar with strong BAL troughs and no apparent broad emission lines in the observed optical range.

It is not surprising that systems with large ejection velocities are discovered when searching for dust-obscured quasars (e.g. [Sprayberry & Foltz 1992](#)). If our redshift measurement based on the spatially extended line is correct the system must be an extreme example of a detached low-ionisation BAL quasar. The onset of the main BAL trough is at a blue-shift of more than  $22\,000\text{ km s}^{-1}$  and the trough extends to about  $40\,000\text{ km s}^{-1}$ . Ejection velocities as large as  $0.1\text{--}0.2c$  are not unheard of in BAL quasars (e.g. [Srianand & Petitjean 2001](#); [King & Pounds 2015](#); [Rogerson et al. 2016](#); [Hamann et al. 2018](#)), but  $40\,000\text{ km s}^{-1}$  is clearly in the high end of the distribution.

This interpretation depends critically on the accuracy of the systemic redshift. The evidence for a systemic redshift of  $z = 2.66$  mainly consists of the presence of the spatially extended and kinematically broad emission line at  $4450\text{ \AA}$ , which we interpret as being due to Lyman- $\alpha$ . It would be very interesting to study this extended emission further using integral field spectroscopy. Supportive evidence for a systemic redshift of  $z = 2.66$  is (i) the presence of narrow absorption lines, which is consistent with the onset of Lyman- $\alpha$  forest absorption at larger redshifts than  $z = 2.41$ ; (ii) possible weak emission lines, which is consistent with Fe III and C III] at  $z = 2.66$ , (iii) the structure of the spectral energy distribution around the *z*- and *Y* bands confirmed by the NOT spectrum is consistent with a BAL trough bluewards of a bright Mg II emission, which is also consistent with  $z = 2.66$ ; and (iv) the LIRIS spectrum that excludes strong H $\alpha$  emission at  $z = 2.41$  and shows tentative evidence for an H $\alpha$  line at  $z = 2.66$ .

An important fact about the source is that it is very red. To match the overall shape of the spectrum as well as the UKIDSS photometry extending to the *K* band, we need to include an extinction of  $A_B = 0.55$ . The BAL quasars constitute about 10–20% of optically selected quasars, but BAL quasars are much more frequent among reddened quasars. [Allen et al. \(2011\)](#) also find an intrinsic BAL fraction in excess of 40% based on analysis of the SDSS quasar catalogue and a modelling of selection criteria. In our own surveys for reddened quasars we have found about half to be BAL quasars ([Krogager et al. 2015, 2016](#)).

Also, the absence of broad emission lines, which are normally observed in type I quasars, is remarkable. However, weak or absent broad emission lines is not unusual for detached BAL quasars ([Hartig & Baldwin 1986](#)).

Interestingly, [Hutsemekers et al. \(1998\)](#) and [Lamy & Hutsemekers \(2004\)](#) established an anti-correlation between the degree of polarisation and the magnitude of the detachment of the BALs. This anti-correlation is particularly strong for low-ionisation BALs such as GQ 1309+2904. A way to test the validity of the systemic redshift proposed in this work is to measure the degree of polarisation. This should be relatively easy given that the quasar is luminous. If we are correct in establishing a systemic redshift of  $z = 2.66$ , then the prediction from [Hutsemekers et al. \(1998\)](#) and [Lamy & Hutsemekers \(2004\)](#) is that the source should not be strongly polarised.

The presence of a large Lyman- $\alpha$  emitting halo around a galaxy hosting a BAL quasar is interesting in itself. It is an interesting question whether a quasar with so strong BALs is capable of releasing enough ionising radiation to illuminate the surrounding circumgalactic medium as in the case of other quasars unless the BAL region is “clumpy” and not covering the full solid angle around the quasar. Studies of the nearby BAL quasar MRK 231 by [Veilleux et al. \(2013, 2016\)](#) have provided strong evidence that (at least some) BAL outflows indeed are patchy/clumpy, as might be required to explain the properties of the present BAL quasar. Moreover, in the models for BAL quasars discussed in for example [Lamy & Hutsemekers \(2004\)](#) and [Veilleux et al. \(2013, 2016\)](#), the viewing angle plays a central role in determining whether we see a P-Cygni type BAL quasar or a detached BAL quasar like GQ 1309+2904. However, the extended Lyman- $\alpha$  emission is most likely far less dependent on viewing angle given its large spatial extent (tens of kpc).

The existence of an extended Lyman- $\alpha$  emission halo also has consequences for the evolutionary state of the system. The lifetime of the quasar must be large enough to allow the setup of a large Lyman- $\alpha$  emitting halo, which sets a lower limit of the order of  $10^5$  years simply based on the light-travel time across the halo. Finally, to our knowledge, this is the first case of a systemic-redshift measurement based on extended Lyman- $\alpha$  emission of a BAL quasar. This method should also be useful in cases of sufficiently distant BL Lac quasars with a priori unknown redshifts.

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