FIRST LONG-TERM OPTICAL SPECTRAL MONITORING OF A BINARY BLACK HOLE CANDIDATE E1821+643. I. VARIABILITY OF SPECTRAL LINES AND CONTINUUM

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ABSTRACT

We report the results of the first long-term (1990–2014) optical spectrophotometric monitoring of a binary black hole candidate QSO E1821+643, a low-redshift, high-luminosity, radio-quiet quasar. In the monitored period, the continua and Hγ fluxes changed about two times, while the Hβ flux changed about 1.4 times. We found periodical variations in the photometric flux with periods of 1200, 1850, and 4000 days, and 4500-day periodicity in the spectroscopic variations. However, the periodicity of 4000–4500 days covers only one cycle of variation and should be confirmed with a longer monitoring campaign. There is an indication of the period around 1300 days in the spectroscopic light curves, buts with small significance level, while the 1850-day period could not be clearly identified in the spectroscopic light curves. The line profiles have not significantly changed, showing an important asymmetry and red line peak redshifted around +1000 km s⁻¹. However, Hβ shows a broader mean profile and has a larger time lag (τ ≈ 120 days) than Hγ (τ ≈ 60 days). We estimate that the mass of the black hole is ∼2.6 × 10⁶M☉. The obtained results are discussed in the frame of the binary black hole hypothesis. To explain the periodicity in the flux variability and high redshift of the broad lines, we discuss a scenario where dense, gas-rich, cloudy-like structures are orbiting around a recoiling black hole.

Key words: galaxies: active – line: profiles – quasars: emission lines – quasars: individual (QSO E1821+643)

Supporting material: machine-readable tables

1. INTRODUCTION

Remarkable features in the optical spectrum of quasars are very broad emission lines that very often show variability in the flux and shape. With the monitoring of these lines, one can investigate the structure of the emitting gas (the broad-line region, BLR; see, e.g., Sulentic et al. 2000; Shapovalova et al. 2010; Popović et al. 2011) and the mass of the supermassive black hole (SMBH) that resides in the center of quasars (see, e.g., Peterson 2014) and study the signatures of galactic evolution, that is, the black hole merger effects (see, e.g., Bon et al. 2012; Popović 2012; Bogdanović 2015).

QSO E1821+643 is one of the most luminous, radio-quiet quasars in the local universe (z = 0.297, mV = 14.2, Mν = −27.1), first detected as an unusually very strong soft X-ray emitter (Pravdo & Marshall 1984; Russell et al. 2010). The multiwavelength observations (from the X-ray to infrared) by Kolman et al. (1993) gave the spectral energy distribution following a power law (α = 1.16) mainly in the IR and X-ray, while the strong optical/UV “blue bump” was modeled with the thermal accretion disk, yielding the mass of the central SMBH of 3 × 10⁹M☉ and an accretion rate of 19 M☉ yr⁻¹ (Kolman et al. 1993). E1821+643 exhibits a remarkable UV/optical/IR emission-line spectrum (Kolman et al. 1991; Kollatschny et al. 2006; Landt et al. 2008) with very broad emission lines (line widths >5000 km s⁻¹), where absorption lines are also seen in the UV (Lyα, C IV, and O IV lines), which may be due to absorption by the gas associated with the quasar (Bahcall et al. 1992; Oegerle et al. 2000).

Even though it has many features usually seen in radio-loud quasars (a high luminosity, an elliptical host galaxy, a surrounding cluster of Abell richness class >2), this object is marked as radio-quiet based on its radio and nuclear [O II] line luminosity (Lacy et al. 1992). The milliarcsecond-resolution radio images of this radio-quiet quasar showed that its compact radio emission is produced by a black hole-based jet, rather than a starburst (Blundell & Lacy 1995; Blundell et al. 1996), while the deep Very Large Array observations revealed a radio emission over 280 h⁻¹ kpc, extended far beyond the host galaxy (Blundell & Rawlings 2001).

The object is embedded in a large elliptical galaxy of Mgal ≈ 2 × 10¹² M☉ (McLeod & McLeod 2001; Floyd et al. 2004) that is associated with a rich cluster of galaxies (Hutchings & Neff 1991), and most likely it resides in its center (Schneider et al. 1992). There are some indications that the quasar SMBH interacts with the surrounding intracluster medium (see in more detail Oegerle et al. 2000; Reynolds et al. 2014; Walker et al. 2014).

The off-nuclear optical spectrum has shown an extended emission-line gas, with the [O III] luminosity about two orders of magnitude higher than in other radio-quiet QSOs (Fried 1998). This extranuclear gas is probably due to tidal interactions or merger processes (Fried 1998). Also, Aravena et al. (2011) observed the 12CO J = 1–0 emission line in E1821+643 and found that the CO emission is likely to be extended, showing a high asymmetry with respect to the center of the host elliptical where the QSO resides. This also suggests that the CO emission may be connected with merger effects: it
may come from a gas-rich companion galaxy in merger, or it may be a tail-like structure from a previous interaction (Aravena et al. 2011). Moreover, the broad emission Balmer lines show an unusual shape. They have highly red asymmetric profiles and at the same time are redshifted (∼1000 km s⁻¹) relative to the narrow lines (Landt et al. 2008; Robinson et al. 2010), which may be caused by the emission of one active component of a binary SMBH or a recoiling black hole after SMBH collision (see Popović 2012). Robinson et al. (2010) analyzed the spectropolarimetric observations of E1821+643 and found that the central SMBH is itself moving with a velocity of ∼2100 km s⁻¹ relative to the host galaxy, which indicates a gravitational recoil that follows the merger of a SMBH binary system.

Here we present the long-term (1990–2014) optical spectrophotometric monitoring of QSO E1821+643, which is the first monitoring campaign for this object. The motivations for long-term observations were (as a summary of the discussion above) that E1821+643 (1) is a very bright quasar located in the (center of) a galaxy cluster; (2) is hosted in an elliptical galaxy, but is a radio-quiet object; (3) has an SMBH that probably interacts with the surrounding intracluster medium; and (4) is probably experiencing a black hole merger (reminiscent of a previous black hole merger or a current supermassive binary black hole interaction). All these facts draw attention to E1821+643 to be monitored with the aim of finding some specific behaviors in the optical spectral variation (in the continuum and line fluxes) and investigating the nature of this object.

In this paper (Paper I), we present photometric and spectroscopic observations of QSO E1821+643, analyzing variability in the Hα and Hβ lines and continuum fluxes. In the forthcoming paper (Paper II), we will give a detailed analysis of the broad line parameters, spectral energy distribution, and Balmer continuum variabilities. The structure of this paper is as follows: in Section 2 we describe the observations and reduction of the observed data, in Section 3 we analyze the observed spectral data and give results, in Section 4 the obtained results are discussed, and in Section 5 we present our main conclusions.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Photometry

The photometry in BVR filters of E1821+643 was performed at the Special Astrophysical Observatory of the Russian Academy of Science (SAO RAS) during the 2003–2014 period (98 nights) with the 1 m Zeiss telescope with an offset guided automatic photometer. The photometer contains a CCD camera of the size 1040 × 1160 pixels, which is cooled with liquid nitrogen (Amirkhanian et al. 2000). The pixel scale at the CCD is 0.′′45/pixel, which corresponds to a 7.5 × 8.5 arcmin field of view. Both bias and dark current frames were taken, while for the flat-field frames we adopted the morning and evening sky exposures. The software developed at SAO RAS by Vlasyuk (1993) was used for the data reduction. The photometry is done by integrating the signal in concentric circular apertures of increasing size, which are centered at the baricenter of the measured object. The photometric system of this instrument resembles those of Johnson in the B and V filters and of Cousins in the R filter (Cousins 1976). For local photometric standards we used the stars of Penston et al. (1971) that are close to the position of E1821+643 on our CCD images, which results in negligible effects of differential air mass. In Table 1 (available electronically only) the photometric BVR-magnitude data for the aperture of 15″ are presented, and in Figure 1 we plotted the light curve in the R band.

2.2. Spectral Observations

Spectra of E1821+643 (~140 nights) were acquired with two telescopes (6 m and 1 m) at SAO RAS, Russia (during 1998–2014), one telescope (INAOE’s 2.1 m) at Guillermo Haro Observatory (GHO) Cananea, Sonora, México (during 1998–2007 and 2013), and two telescopes (3.5 m and 2.2 m) at Calar Alto Observatory, Spain (during 1990–1994). All spectra were acquired with long-slit spectrographs with CCDs. The representative wavelength interval was from 4000 to 7500 Å, with a spectral resolution between 4.5 and 15 Å and a signal-to-noise ratio (S/N) >50 in the continuum close to the Hβ line. Every night the spectrophotometric standard stars were observed. Information on the source of spectral observations is listed in Table 2, while the log of spectral observations is listed in Table 3 (available electronically only).

The spectrophotometric data reduction was performed using the software developed at SAO RAS, while for the spectra acquired in Mexico and in Spain the IRAF package was used. The image-reduction procedure consisted of the standard bias and flat-field corrections, cosmic ray removal, 2D wavelength linearization, sky spectrum subtraction, addition of the spectra for every night, and relative flux calibration based on a standard star. Later in the analysis, we rejected approximately 10% of the spectra for various reasons, such as poor spectral resolution (>15 Å), a high noise level, and badly corrected spectral sensitivity. Thus our final data set contains 127 spectra that are further analyzed.

2.3. Absolute Calibration (Scaling) of the Spectra

The common technique of spectral flux calibration based on a comparison with stars of determined spectral energy distribution is not precise enough for the study of active galactic nucleus (AGN) variability because the spectrophotometric accuracy is not less than 10% even under great photometric conditions. Thus the standard stars were only used for a relative flux calibration. For the absolute calibration, the AGN narrow emission line fluxes were used to scale the spectra because it is noted that these lines do not vary on timescales of decades (Peterson 1993).

E1821+643 is a QSO with very bright [O III] λλ4959, 5007 emission lines, and it is possible to scale our spectra using the flux of these lines. However, a problem may be that the [O III] lines are varying during the long monitored period of 24 years.

The very bright [O III] emission (two orders of magnitude brighter than in other radio-quiet quasars; see Fried 1998) indicates the presence of a very large narrow line region (NLR). Taking the relation $R_{\text{NLR}} \approx L_{\text{[OIII]}10.33}$ given by Schmitt et al. (2003) and the $[\text{O III}] \lambda \lambda 4959, 5007\lambda$ flux of the order of $\sim 2 \times 10^{-13}$ erg cm⁻² s⁻¹ for E1821+643 ($z \approx 0.3$), we estimated that the size of the extended NLR is of the order of ~8 kpc (26,000 light years), which is three orders of magnitude larger than our monitored period (24 years), so one cannot expect to detect the variability in the [O III] line flux during this monitored period.
Table 1

|   | UT date   | MJD 2400000 | Seeing (arcsec) | $M_R \pm \sigma$ | $M_V \pm \sigma$ | $M_{\lambda} \pm \sigma$ |
|---|-----------|-------------|-----------------|------------------|-----------------|------------------|
| 1 | 28.06.2003 | 52818.4     | 3.0             | 13.964 ± 0.027   | 15.230 ± 0.030  | 14.413 ± 0.015   |
| 2 | 30.06.2003 | 52820.5     | 3.0             | 13.965 ± 0.036   | 15.212 ± 0.028  | 14.431 ± 0.014   |
| 3 | 31.07.2003 | 52852.4     | 2.0             | 13.996 ± 0.028   | 15.726 ± 0.028  | 14.445 ± 0.009   |
| 4 | 26.08.2003 | 52877.4     | 2.3             | 13.980 ± 0.036   | 14.437 ± 0.025  | 14.443 ± 0.026   |
| 5 | 01.10.2003 | 52913.4     | 1.8             | 13.967 ± 0.036   | 15.283 ± 0.014  | 14.413 ± 0.015   |

Note. Column (1): number. Column (2): UT date. Column (3): Modified Julian Date. Column (4): mean seeing in arcsec. Columns (5)–(7): BRV magnitudes and the corresponding errors.

(This table is available in its entirety in machine-readable form.)

![Figure 1](image.png)

Figure 1. R-band light curve for the observed and interpolated data. The four maxima are denoted on the plot. The error bars are comparable to the symbol size.

Table 2

| Observatory                                      | Code | Tel/Aperture + Equipment | Aperture (arcsec) | Focus |
|-------------------------------------------------|------|--------------------------|-------------------|-------|
| SAO (Russia)                                    | L(N) | 6 m + Long slit          | 2.0 × 6.0         | Nasmith |
| SAO (Russia)                                    | L(U) | 6 m + UAGS               | 2.0 × 6.0         | Prime  |
| SAO (Russia)                                    | L(Sc)| 6 m + Scorpio            | 1.0 × 6.07        | Prime  |
| Guillermo Haro Observatory (México)             | GHO  | 2.1 m + B&C              | 2.5 × 6.0         | Cassegrain |
| SAO (Russia)                                    | Z1   | 1 m + GAD                | 4.0 × 19.8        | Cassegrain |
| SAO (Russia)                                    | Z2   | 1 m + GAD                | 4.0 × 9.45        | Cassegrain |
| Calar Alto (Spain)                              | CA1  | 3.5 m + B&C / TWIN       | 2.0 × 4.0         | Cassegrain |
| Calar Alto (Spain)                              | CA2  | 2.2 m + B&C              | 2.0 × 4.0         | Cassegrain |

Note. Column (1): observatory. Column (2): code assigned to each combination of telescope + equipment used throughout this paper. Column (3): telescope aperture and spectrograph. Column (4): projected spectrograph entrance apertures (slit width × slit length in arcsec). Column (5): focus of the telescope.

Therefore, we used the [O III]4959+5007 integrated line flux, which is taken to be $2.9 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (Kolman et al. 1993), in order to absolutely calibrate our spectra with the method proposed by Van Groningen & Wanders (1992) as modified by Shapovalova et al. (2004). Note that this method was tested for different S/N > 20 and different spectral resolutions, and it has been shown that the uncertainty in the scaling is ~1%–2% and depends only on the quality of the spectra. For more details, see Van Groningen & Wanders (1992) and Appendix A in Shapovalova et al. (2004).

2.4. Unification of the Spectral Data

For the study of the long-term spectral variability of an AGN observed with telescopes of different apertures, it is mandatory to construct a uniform data set in a consistent way. Since instruments of different apertures were used for the observations, it is necessary to correct both the continuum and line fluxes for aperture effects (Peterson & Collins 1983). Based on our past work (Shapovalova et al. 2001, 2004, 2010, 2012, 2013), we determined a point-source scale correction factor ($\phi$) and an aperture-dependent correction factor that corrects for the
host galaxy contribution to the continuum, that is, an extended-
source correction factor \( (G(g)) \). We used the following
expressions (see Peterson et al. 1995):

\[
F(\text{line})_{\text{true}} = \varphi \times F(\text{line})_{\text{obs}}, \\
F(\text{cont})_{\text{true}} = \varphi \times F(\text{cont})_{\text{obs}} - G(g),
\]

where the index “obs” denotes the observed flux and “true” the
aperture-corrected flux. The spectra of the 6 m telescope within
an aperture of \( 2'' \times 6'' \) were adopted as standard (i.e., \( \varphi = 1.0 \),
\( G(g) = 0 \) by definition). The correction factors \( \varphi \) and \( G(g) \) are
estimated empirically, comparing the observations from all
telescope data sets with the simultaneous one from the standard
data set (the same method was used in AGN Watch; see, e.g.,
Peterson et al. 1994, 1998, 2002). Intervals that we noted as
“nearly simultaneous” are practically 1–3 days, suppressing the
variability on short timescales (<3 days). The point-source
scale correction factor \( \varphi \) and extended-source correction factor
\( G(g) \) values (in units of \( 10^{-15} \text{ erg cm}^{-2} \text{s}^{-1} \text{ Å}^{-1} \)) are given for
different data sets in Table 4.

### 2.5. Measurements of the Spectral Fluxes and Errors

From the scaled spectra (see Sections 2.2–2.3), we measured
the continuum flux near the H\( \beta \) line at the observed wavelength
\( \sim 6616 \text{ Å} \) (\( \sim 5100 \text{ Å} \) in the rest frame) by averaging fluxes in the
spectral range of \( 6601–6631 \text{ Å} \), and the continuum flux near the
H\( \gamma \) line at the observed wavelength \( \sim 5474 \text{ Å} \) (\( \sim 4220 \text{ Å} \) in
the rest frame) by averaging fluxes in the spectral range of
\( 5459–5489 \text{ Å} \). Note that the spectrum of E1821+643 does not
contain significant absorption lines in the observed spectral
range (see Figure 2).

For the determination of the H\( \beta \) and H\( \gamma \) fluxes, we must first
subtract the underlying continuum. For this goal, a linear
continuum was fitted through the windows of \( 20 \text{ Å} \) and
\( 6160–6635 \text{ Å} \) for the H\( \beta \) region and \( 5480–5780 \text{ Å} \) for the H\( \gamma \)
region. Then, the observed line fluxes were measured in the
following wavelength intervals: \( (6170–6620) \text{ Å} \) for H\( \beta \) and
\( (5550–5770) \text{ Å} \) for H\( \gamma \). Using the \( \varphi \) and \( G(g) \) factors from
Table 4, we recalibrated the observed \( H \gamma \) and H\( \beta \) fluxes and
their corresponding nearby continuum fluxes to a common
scale using the standard aperture of \( 2'' \times 6'' \). In Table 5
(available electronically only) the fluxes for the continuum at
the rest-frame wavelength of \( 5100 \) and \( 4220 \text{ Å} \), the total H\( \gamma \) and
H\( \beta \) lines, and their errors are given. The listed total H\( \gamma \) and H\( \beta \)
fluxes include the contribution of the narrow H\( \gamma \) and H\( \beta \)
components and the [O III] 4363, 4959, 5007 lines. The mean
errors (uncertainties) of the continuum fluxes at \( 5100 \text{ Å} \) and
\( 4220 \text{ Å} \) H\( \beta \) and the H\( \gamma \) lines are \( \sim (2–3.5\%) \), \( \sim (3.5\%) \), and \( \sim 5\% \),
respectively (see Table 6). These quantities were estimated by
comparing the results from spectra obtained within a time
interval shorter than 3 days. Note that the errors in fluxes in
Table 5 were obtained using the mean error from Table 6.

Figure 3 shows mean errors in the flux measurements as a
function of the corresponding mean line fluxes for H\( \beta \) and H\( \gamma \),
and for the continuum at \( 5100 \) and \( 4220 \text{ Å} \). The correlation

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**Table 3**

| \( N \) | UT date | MJD | CODE\(^a\) | Aperture \( (\text{arcsec}) \) | Sp. range \( (\text{Å}) \) | Seeing \( (\text{arcsec}) \) |
|---|---|---|---|---|---|---|
| 1 | 23.07.1990 | 48095.0 | CA1 | 2.0 × 4.0 | 6060–7690 | 1.5–2.5 |
| 2 | 07.08.1991 | 48476.0 | CA2 | 2.0 × 4.0 | 5170–7650 | 1.5–2.5 |
| 3 | 10.08.1991 | 48479.0 | CA2 | 2.0 × 4.0 | 5540–7640 | 1.5–2.5 |
| 4 | 09.07.1992 | 48813.0 | CA1 | 2.0 × 4.0 | 5510–7690 | 1.5–2.5 |
| 5 | 25.08.1992 | 48860.0 | CA2 | 2.0 × 4.0 | 3850–7650 | 1.5–2.5 |

Note. Column (1): number. Column (2): UT date. Column (3): Modified Julian Date. Column (4): CODE\(^a\). Column (5): projected spectrograph entrance apertures. Column (6): wavelength range covered. Column (7): mean seeing in arcsec.

\(^a\) Code given according to Table 2.

(This table is available in its entirety in machine-readable form.)

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**Table 4**

| Sample | Aperture \( (\text{arcsec}) \) | Scale Factor \( (\varphi) \) | Extended Source Correction \( G(g) \) |
|---|---|---|---|
| L(U, N) | 2.0 × 6.0 | 1.000 | 0.000 |
| L(Sc) | 1.0 × 6.07 | 0.976 | −0.414 |
| GHO | 2.5 × 6.0 | 0.951 | 0.000 |
| Z1 | 4.0 × 19.8 | 0.958 ± 0.017 | 0.280 ± 0.166 |
| Z2 | 4.0 × 9.45 | 1.048 | 0.033 |
| CA1 | 2.0 × 4.0 | 1.000 | 0.000 |
| CA2 | 2.0 × 4.0 | 1.000 | 0.000 |

\(^a\) Note. In units of \( 10^{-15} \text{ erg cm}^{-2} \text{s}^{-1} \text{ Å}^{-1} \).
Table 5
Measured Line and Continuum Fluxes

| N | UT date   | MJD       | $F_{S100} \pm \sigma$ | $F(H\beta) \pm \sigma$ | $F(4200) \pm \sigma$ | $F(H\gamma) \pm \sigma$ |
|---|-----------|-----------|------------------------|------------------------|------------------------|------------------------|
| 1 | 23.07.1990| 48095.0   | 5.23 ± 0.12            | 11.58 ± 0.34           | 7.58 ± 0.24            | 2.60 ± 0.14            |
| 2 | 07.08.1991| 48476.0   | 5.59 ± 0.13            | 11.29 ± 0.33           | 7.34 ± 0.24            | 2.34 ± 0.12            |
| 3 | 10.08.1991| 48479.0   | 5.42 ± 0.13            | 10.81 ± 0.32           | 7.20 ± 0.23            | 2.28 ± 0.12            |
| 4 | 09.07.1992| 48813.0   | 5.19 ± 0.12            | 11.65 ± 0.34           | 6.50 ± 0.21            | 2.39 ± 0.12            |
| 5 | 25.08.1992| 48860.0   | 5.50 ± 0.13            | 12.32 ± 0.36           | 12.36 ± 0.40           | 2.84 ± 0.15            |

Table 6
Estimates of the Mean Errors for $H\beta$ and $H\gamma$ Total-line Fluxes and for $H\beta$ Broad-line Segment Fluxes

| Line  | Spectral Region (Å) (obs) | Spectral Region (Å) (rest) | $\sigma \pm e$ (%) | $V_r$ Region km s$^{-1}$ | $|V_{rest} - V_{phabs}|$ km s$^{-1}$ |
|-------|---------------------------|-----------------------------|-------------------|--------------------------|-------------------------------|
| cont 5100 | 6601–6633                     | 5089–5111                     | 2.3 ± 2.0         | ...                     | ...                           |
| cont 4200 | 5459–5489                     | 4208–4231                     | 3.2 ± 2.1         | ...                     | ...                           |
| $H\beta$—total | 6170–6620                     | 4756–5103                     | 2.9 ± 2.1         | (−6423)–(+14988)       | 21411                         |
| $H\gamma$—total | 5550–5770                     | 4278–4448                     | 5.2 ± 3.1         | (−4763)–(+7460)       | 12223                         |
| $H\beta$—broad | 6170–6620                     | 4756–5103                     | 2.9 ± 2.1         | (−6423)–(+14988)       | 21411                         |
| $H\beta$—blue | 6199–6284                     | 4779–4844                     | 4.9 ± 3.8         | (−6089)–(−2091)       | 3998                          |
| $H\beta$—core | 6285–6369                     | 4845–4910                     | 3.1 ± 3.0         | (−2030)–(+1698)       | 3998                          |
| $H\beta$—red | 6371–6456                     | 4911–4977                     | 4.1 ± 3.2         | (+2030)–(+6088)       | 4058                          |
| $H\beta$—far red | 6457–6551                     | 4978–5050                     | 6.0 ± 4.6         | (+6150)–(+10578)      | 4428                          |

Notes. Column (1): measured continuum/line/line segment. Column (2): observed wavelength range. Column (3): rest-frame wavelength range. Column (4): estimated error and its standard deviation. Column (5): velocity range. Column (6): velocity range width.

The redshift used is $z = 0.2972$. The central peak wavelength is 6327 Å in the observed frame (4877.5 Å in the rest frame). The shift relative to the narrow $H\beta$ is 21 Å or 1013 km s$^{-1}$ in the observed frame (16.5 Å or 1018 km s$^{-1}$ in the rest frame).

Figure 3. $H\beta$ line and continuum at 5100 Å flux errors (left panels), and $H\gamma$ line and continuum at 4200 Å flux errors (right panels) with respect to the corresponding mean flux. The continuum flux is in units of $10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$, and the line fluxes are in units of $10^{-13}$ erg cm$^{-2}$ s$^{-1}$.

The contribution of the host galaxy can be very important in some objects (see, e.g., Shapovalova et al. 2013), especially if the stellar absorption lines are present in the AGN spectrum. Therefore we roughly estimated the contribution of the host galaxy from the aperture photometry with apertures 10″ and 15″.

coefficient and corresponding $p$ value are also given in Figure 3. As can be seen, it is obvious that the dependence between the mean error and the mean fluxes does not exist between $F(H\beta)$ and $F(5100)$ or has a very weak trend (statistically insignificant) between $F(H\gamma)$ and $F(4200)$.
One can expect that in the ring between 15′ and 10′ the flux in the V and R filters is from the host galaxy, so we used the ratio of the ring flux to the 10′-aperture flux to estimate the host-galaxy contribution. We obtained that the contribution of the host galaxy in the V band is from 3.0% to 4.6%, relative to the flux in the maximum and minimum activity states of the nucleus, respectively. In the R band, the host-galaxy contribution is from ~3% to 9%. This does not contradict an estimate made in the V band by Floyd et al. (2004) from the modeling of an HST/WFPC2 image of this object. They found that the host galaxy contributed around ~10% to the total luminosity in the V band in 2000 (when the object was close to the minimum state). Also, we should note that in the spectra of E1821+643 the stellar absorption lines such as Mg IIb (5170), Ca ii (H,K), and the G band (4302) are absent, which indicates a very small host-galaxy contribution.

2.6. The Broad Hβ Line and Its Segment Fluxes

In this paper we will extract only the broad component of the Hβ line and study the behavior of its line segments during the monitored period. The detailed analysis of the Hβ and Hγ line profiles using the Gaussian fitting method will be given in the forthcoming paper (Paper II).

To obtain only the broad component of the Hβ line, we subtracted the underlying continuum that was fitted through the continuum windows using the B-spline Python routine interpolate.splev. Then we applied an automatic and self-consistent multi-Gaussian fitting method to remove the narrow components of the Hβ, [O iii]λ4959, 5007 Å lines, and Fe ii lines (Popović et al. 2004; Kovačević et al. 2010; Shapovalova et al. 2012). The fitting method is based on the χ²-minimization routine, and we reduced as many Gaussian parameters as possible: (1) all narrow lines have the same widths and shifts (see Popović et al. 2004); (2) the flux ratio of [O iii]λ4959 Å and [O iii]λ5007 Å is 1:3 (Dimitrijević et al. 2007); (3) two broad Gaussian functions (broad and very broad line components) were used to fit the broad Hβ component; (4) the ionized iron line multiplets have lines of the same widths and shifts (Kovačević et al. 2010; Shapovalova et al. 2012). One example of the best fit (thick solid line) of the observed spectrum (dots) is presented in the upper panel of Figure 4, where the 42 Fe ii multiplet (dashed line) is also shown. The residual (thin solid line) and the Gaussian broad and narrow components (dashed lines) are shifted below for better visibility (Figure 4). Note here that only one Gaussian cannot properly fit the narrow line wings of strong [O iii] lines, so we included an additional, broader Gaussian (with significantly smaller intensity) to fit the narrow [O iii] line wings.

We determined the flux of the broad Hβ component in the same wavelength range as for the total Hβ line and estimated that the contribution of the narrow components is ~30%. We also found that the peak of the broad Hβ component is shifted by ~1000 km s⁻¹ relative to the peak of the narrow component. Measuring the flux of the broad Hβ line segments, we divided the broad Hβ component relative to the shifted center (4877.5 Å in the rest frame) into four line segments with a width of ~4000 km s⁻¹ each: blue wing, core, red wing, and far red wing (see the bottom panel in Figure 4 and Table 6). Then we determined the fluxes of these line segments (Table 7, available electronically only). The mean errors for the broad Hβ line-segment fluxes are about 3%–6% (Table 6).

As expected, the maximal error of ~6% corresponds to the distant, far-red wing and is caused by a bad subtraction of the bright [O iii]λ5007 Å line and a weak line intensity in this spectral region. The mean errors (in %) of fluxes and the line-segment fluxes are given in Table 6 and in Table 7 (available electronically only), respectively.

3. DATA ANALYSIS AND RESULTS

3.1. Photometric Results

In Table 1 the results of the broadband photometry of E1821+643 in BVR filters for a circular aperture of 15″ and the corresponding errors are listed. A light curve in the R band shows an almost sinusoidal change with a maximum amplitude of about 0.5 mag (see Figure 1). There, we can see several (about four) noticeable peaks (flares, outbursts) with different brightness amplitudes. In the BV bands the light curves have the same shape. Some information about these flare-like events is listed in Table 8. It follows that the amplitude of the peaks varies from 0.1 to 0.54 mag, or in intensity from 1.1 to 1.6 times. It is very interesting to note that the difference in days between the two consecutive flare-like events is ~1000 days (Table 8). This indicates some periodicity in the flux variability during the monitored period. Later (in Section 3.2.4) we study the periodicity of light curves using different methods.

3.2. Spectral Results

Figure 2 shows typical spectra of E1821+643 observed close to the minimum and maximum activity during the monitored period. It is obvious that in the spectra of E1821+643 the broad emission lines of the hydrogen Balmer series
and the big blue bump are most outstanding. Also, the narrow components of the Balmer lines and various forbidden lines typical of AGNs (the most prominent [O iii]4959+5007 lines) are observed. As can be seen in Figure 2, there is no dramatic change in the spectral energy distribution and Balmer continuum between the minimum and maximum stages. Using the narrow line components, we obtained an average redshift of $z = 0.2972 \pm 0.0002$, which we take as the rest frame of the host galaxy. We confirmed, as other authors found as well (see Landt et al. 2008; Robinson et al. 2010, etc.), that the peaks of the broad Balmer line components are redshifted with respect to the narrow line components by $-1000$ km s$^{-1}$. The broad Balmer lines have extremely asymmetric profiles, with red wings extending to Doppler velocities of at least $\sim 15,000$ km s$^{-1}$ relative to the rest-frame wavelength (Table 6).

3.2.1. Variability of the Emission Lines and the Optical Continuum

We analyzed flux variations in the continuum and lines using a total of 127 and 76 spectra covering the H$\beta$ and H$\gamma$ wavelength regions, respectively. In Table 5 the fluxes in continua at 5100 and 4200 Å and total H$\beta$ and H$\gamma$ lines are listed. Using these data, we plotted the light curves for the continuum at the rest wavelengths 5100 and 4200 Å and for the H$\beta$ and H$\gamma$ lines (see Figure 5). It is obvious that the fluxes in the continua and lines are varying during this monitored period (1990–2014). In the continuum light curves, and with some possible delay in the H$\beta$ and H$\gamma$ light curves, the same flare-like events (1–3 from Table 8) as in the R-band photometric light curve (see Figure 1) are seen. In Figure 6 the light curves for the broad H$\beta$ line component and its different line segments are given. Both fluxes in the broad H$\beta$ line component and in its line segments (blue, core, red+far red, Table 7) vary quasi-simultaneously, and local maxima, approximately close to the flare-like events 1–3, are also traced. In Figure 6, there are some indications of the presence of the shorter-timescale fluctuations (flares) in the light curves of the total-line and line-segment fluxes. These flare-like features become clearer in the artificially generated light curves (see Section 4.1). One can expect that a fraction of short-time flares arise from the uncertainties in the relative flux calibration (i.e., unification of the spectral data; see Sections 2.4 and 2.5); however, the short-time flares can also be detected in the spectrophotometric curves as a consequence of the short time variability of the nucleus. For example, in several other objects, the short-time flares have been registered in the line or continuum light curves (e.g., Ark 564 and Arp 102B, see Shapovalova et al. 2012, 2013). In the case of this object, the short-time flares are not within the frame of the error bars, so it seems that from time to time the short-time flare events are present in the light curves of E1821+643.

For the variability estimates of the line and continuum fluxes, we used the method given by O’Brien et al. (1998). In Table 9 we give parameters that describe the variability of the continuum and total line fluxes: $N$ is the number of spectra, $F$ denotes the mean flux over the whole observing period and $\sigma (F)$ is the standard deviation, and $R(\text{max}/\text{min})$ is the ratio of the maximal to minimal flux in the monitoring period. The parameter $F(\text{var})$ is an inferred (uncertainty-corrected) estimate of the variation amplitude with respect to the mean flux, defined as

$$F(\text{var}) = \sqrt{\frac{\sigma(F)^2 - e^2}{N}}/F(\text{mean})$$

with $e^2$ being the mean square value of the individual measurement uncertainties for $N$ observations, i.e., $e^2 = \frac{1}{N}\sum_{i=1}^{N} e(i)^2$ (O’Brien et al. 1998). From Table 9 it follows that the fluxes in the continuum (at rest 5100 and 4200 Å) and the total H$\gamma$ line changed about two times, and in the H$\beta$ flux only $\sim 1.4$ times. The difference in the line flux variations between H$\beta$ and H$\gamma$ may be caused by different dimensions of the emitting region for these two lines (the H$\gamma$-emitting region

| $N$ | UT date | MJD 240000 | Amplitude (m) | $I_{\text{max}}/I_{\text{min}}$ | $\text{maxJD}(i+1)-\text{maxJD}(i)$ (days) |
|-----|---------|------------|---------------|-------------------------------|---------------------------------------------|
| 1   | 2005 Nov 28 | 53703 | 0.54          | 1.6                           | 1066 (2–1)                                 |
| 2   | 2008 Oct 29 | 54769 | 0.10          | 1.1                           | 1030 (3–2)                                 |
| 3   | 2011 Aug 26 | 55799 | 0.17          | 1.17                          | 1002 (4–3)                                 |
| 4   | 2014 May 23 | 56801 | 0.10          | 1.1                           | ...                                        |

Note. Column (1): number of flare-like events. Column (2): UT date. Column (3): Modified Julian Date. Column (4): approximate amplitude between maximum and minimum (in magnitudes) for a flare-like event. Column (5): the ratio of the maximum to minimum intensity. Column (6): the difference in days between the two relevant events (in parentheses).

Table 7

| $N$ | MJD 240000 | $F(\text{H}\beta)_{\text{broad}}$ | $F(\text{H}\beta)_{\text{blue}}$ | $F(\text{H})_{\text{core}}$ | $F(\text{H})_{\text{red}}$ | $F(\text{H})_{\text{far Red}}$ |
|-----|------------|-------------------------------|-------------------------------|-----------------------------|-----------------------------|-------------------------------|
| 1   | 48095.00   | 7.171 ± 0.205                | 0.861 ± 0.042                | 3.672 ± 0.114              | 1.838 ± 0.075              | 0.704 ± 0.042                |
| 2   | 48476.00   | 6.979 ± 0.200                | 0.822 ± 0.040                | 3.714 ± 0.115              | 1.731 ± 0.071              | 0.638 ± 0.038                |
| 3   | 48479.00   | 6.427 ± 0.184                | 0.673 ± 0.033                | 3.466 ± 0.107              | 1.563 ± 0.064              | 0.603 ± 0.036                |
| 4   | 48813.00   | 7.235 ± 0.207                | 0.763 ± 0.037                | 3.806 ± 0.118              | 1.910 ± 0.078              | 0.717 ± 0.043                |
| 5   | 48860.00   | 7.702 ± 0.220                | 0.805 ± 0.040                | 4.024 ± 0.125              | 1.960 ± 0.080              | 0.802 ± 0.048                |

(This table is available in its entirety in machine-readable form.)
is significantly smaller than the \( \text{H}\beta \) one). In addition, the smaller variability in the \( \text{H}\beta \) flux may be caused by the contribution of the constant fluxes from narrow lines \([\text{O iii}]\) 4949, 5007. The amplitude of variability \( F(\text{var}) \) is \(~19\%\) for the continuum and total \( \text{H}\gamma \) line and \(~7\%\) for the total \( \text{H}\beta \) line. The fluxes of the broad \( \text{H}\beta \) segments (blue, red, far-red wings, and core) vary quasi-simultaneously with \( F(\text{var}) \sim 11\%–12\% \) (Table 9, Figure 6).
The correlation of the blue wing and continuum

depends on the Hβ—core and red wing.

There are significant correlations ($r = 0.6–0.8$) between the line core and red wing flux with the continuum flux, but the correlation of the blue wing and continuum fluxes is smaller ($r = 0.35$) and less statistically significant.

### 3.2.3. Time-lag Analysis

There are several classes of methods for handling the problem of time-lag analysis for irregular data sets. Perhaps the oldest class of estimators is a standard interpolation (using linear and cubic spline) of observations in order to create a time series on a regularly spaced grid. This method leads to a significant reduction in variance toward the high-frequency range of the estimated power spectrum. When there is an interest in phenomena on smaller timescales (relative to the mean sampling interval), such effects should be taken into account. Beside this, the persistence (memory) of an irregular time series is strongly overestimated when using the standard (linear and cubic spline) interpolation approach (Rehfeld et al. 2011).

Our data sets are irregular, so for the time-lag analysis of the spectroscopic and photometric light curves we applied three methods: (1) the discrete correlation function (DCF; Edelson & Krolik 1988), (2) the z-transformed discrete correlation function (ZDCF; Alexander 1997; 2013), both methods from the class of slotting time-lag estimators, and (3) the stochastic process estimation for AGN reverberation (SPEAR) by Zu et al. (2011), a recently developed method that is a model-based estimator that uses a damped random-walk model (Kelly et al. 2009; Kozlowski et al. 2010; MacLeod et al. 2010). For more details on all three methods and their differences and advantages, see a recent paper by Kovačević et al. (2014) and references therein.

We calculated the DCF and ZDCF functions over the majority of the time range of our monitoring campaign (the points before 1998 are excluded because of extremely poor sampling). The ZDCF lags are taken to be the peaks of the cross correlation functions (CCFs), while the uncertainties are addressed using the Monte Carlo method (Alexander 1997; 2013). The DCF lags, the DCF coefficients, and their errors are calculated using the MATLAB bootstrap toolbox for time series analysis. For this, we constructed 1000 clones of our light curves. Each clone is made by choosing random samples
with replacement from the mother curve; each observation is selected separately at random from the original data set. The number of elements in each bootstrap clone equals the number of elements in the original data set. Then the centroid of DCF was computed for each pair of clones so we can construct bootstrap vectorial statistics of time lags and centroid of DCF. The mean values are chosen as the final DCF lag and coefficient results, and the uncertainties are calculated as standard deviations of their bootstrap distributions.

Since our light curves have large mean sampling, we attempt to probe the time lags of the artificial time series with better sampling and which points are “predictions” obtained from the original time series. For this task, we employed a Gaussian process regression (GPR) for noisy data (Rasmussen & Williams 2006). A GPR generates data such that if we observe their values, they would follow a multivariate Gaussian distribution. The main constituents of a GPR are its covariance and mean functions. With the covariance function we encode correlations (relations or similarities) between different data points in the process. We specified a GPR for our artificial time series as follows: a constant mean function, with initial parameter set to the mean of the original time series, and an

Figure 8. Hβ vs. Hγ flux (upper) and continua 5100 Å vs. 4200 Å flux (bottom). The continuum flux is in units of $10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$, and the line flux in units of $10^{-13}$ erg cm$^{-2}$ s$^{-1}$. Observations with different telescopes are denoted with different symbols given in the upper left. The correlation coefficients and the corresponding $p$ values are also given.

Figure 9. Hβ/Hγ flux ratio vs. continuum flux at 5100 Å. The continuum flux is in units of $10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$. Observations with different telescopes are denoted with different symbols given in the upper right. The correlation coefficients and the corresponding $p$ values are also given.

Figure 10. Broad Hβ component and line-segment fluxes (blue, core, and red) vs. continuum flux at 5100 Å, respectively from top to bottom. The continuum flux is in units of $10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ and the broad Hβ component and line-segment fluxes are in units of $10^{-13}$ erg cm$^{-2}$ s$^{-1}$. The correlation coefficients and the corresponding $p$ values are given in the bottom right corner.
isotropic squared exponential covariance (kernel) function. The covariance function takes two hyperparameters: a characteristic length scale and the standard deviation of the original signal. The length scale was set to 150. Figure 12 gives the comparison between the GPR-generated and observed light curves of the continuum at 5100 Å, Hβ, the continuum at 4200 Å, and Hγ (from top to bottom).

Table 10 summarizes the results of all three time-lag estimators we employed on both the observed and GPR-generated artificial light curves of Hβ and Hγ and the corresponding continuum light curves. The GPR artificial light curves have uniform and better sampling. Figure 13 gives the derived CCFs (triangles) of the Hβ (upper panels) and Hγ (bottom panels) time lags from the DCF (left panels) and ZDCF (middle panels) methods and the equivalent probability distribution from the SPEAR method (right panels). The derived CCFs of the corresponding GPR-generated artificial light curve are also given for comparison. The large number of points in the GPR light curves leads to better-constrained uncertainties in the case of the DCF and ZDCF methods, due to a consequently larger number of binned points.

In the DCF and ZDCF methods, the derived CCFs obtained from the observed light curves (left and middle panels in Figure 13) typically contain two peaks of similar amplitude that (considering the error bars) are not statistically distinguishable. In Table 10 we listed the values of the first clearly visible peak. With this we demonstrated that the reliable lags cannot be recovered directly from these data sets using the DCF and ZDCF methods. Another point that can be seen from Table 10 is that the ZDCF gives for both Hβ and Hγ the time lags that are similar to the median sampling interval and thus might be considered spurious. However, this may also be a coincidence because other authors have obtained time lags similar to the median sampling interval (see, e.g., Denney et al. 2009).

We should also note here that the obtained time lags can be influenced by the relative flux calibration (i.e., unification of the spectral data; see Sections 2.4 and 2.5) of the spectra and the short-time flares, which can be seen in the light curves of the continua and broad lines. The data calibration procedure used in constructing the light curves can affect the traditional CCF analysis and can have a greater effect on the lag analysis of the more sparsely sampled Hγ—continuum light curves. That is why we additionally applied the SPEAR method, which has been tested for different calibration effects, and it has been shown that the impact on the estimated lag is generally negligible (see Zu et al. 2011). Additionally, as can be seen in Figure 12, the GPR procedure allows us to avoid the influence of the flare-like local peaks.

The SPEAR method treats large time gaps in light curves with a statistically based approach and considers the impact on the uncertainties of the time lag. Our data sets have large time gaps in the light curves and flare-like peaks, so the obtained ZDCF and DCF curves are degenerated, whereas the SPEAR time-lag probability distributions are well defined with no deterioration. Therefore the obtained SPEAR lags are preferred.

As a summary of our CCF analysis, we can state that there is a large difference between the Hβ and Hγ time lags obtained from the SPEAR method (in both cases, for the observed and GPR time series). It seems that the Hγ-emitting region is smaller than the Hβ one, which is also in agreement with the dependence of the flux ratio of the lines as a function of the continuum (see Figure 9). Later in this text, we will use the values of lags obtained from the SPEAR method applied on the GPR-generated artificial light curves, that is, the lag for Hβ ~ 120 and for Hγ ~ 60 days.

### 3.2.4. Periodicity

As noted in Sections 3.1 and 3.2.1, three to four maxima are visible in the photometric and spectral light curves (see Figure 1: the maxima are denoted with vertical ticks). This motivated us to search for periodicities in different light curves.

We applied a periodogram analysis to test whether our time series contain only noise or have some periodic components. In the presence of semiperiodic or even nonperiodic components, the periodogram can show more than one prominent peak. Another problem is that the mean values are not always good estimators of the mean of the periodogram’s underlying function, causing problems like aliasing. In order to avoid these problems, we applied several techniques to our time
Figure 12. Comparison between the GPR-generated (dashed line) and observed light curves (circles with error bars) of the continuum at 5100 Å, Hβ, the continuum at 4200 Å, and Hγ (from top to bottom). The shaded band represents the 95% confidence interval (CI) for the GPR predicted curve.

Table 10

| TS  | TS1 | TS2 | ρ̅  | ̂ρ | N  | τ_{ZDCF} | τ_{ZDCF} | τ_{DCF} | τ_{DCF} | τ_{SPEAR} |
|-----|-----|-----|-----|----|----|----------|----------|----------|----------|-----------|
| Observed |     |     |     |    |    |          |          |          |          |           |
| cnt5100 Hβ | 48.7 | 28.6 | 121 | 26.24 | 0.59 ±0.06 | 208 ±11 | 0.72 ±0.02 | 196 ±9 |
| cnt4200 Hγ | 82.3 | 54.9 | 72  | 65.24 | 0.78 ±0.07 | 54 ±19 | 0.56 ±0.16 | 60 ±11 |
| GPR    |     |     |     |    |    |          |          |          |          |           |
| cnt5100 Hβ | 11.7 | 11.7 | 500 | 118.0 ±0.00 | 0.73 ±0.05 | 125.0 ±0.03 | 0.96 ±0.03 | 120.6 ±10.6 |
| cnt4200 Hγ | 11.7 | 11.7 | 500 | 152.3 ±0.01 | 0.90 ±0.01 | 96.0 ±4.0 | 0.96 ±0.02 | 59.3 ±6.6 |

Note. Column (1): TS type. Columns (2) and (3): cross-correlated TS. Columns (4) and (5): mean ̄ρ and median ̂ρ sampling. Column (6): number of points in TS. Column (7): time lag calculated using ZDCF method. Column (8): cross-correlation coefficient calculated using ZDCF. Column (9): time lag calculated using DCF. Column (10): cross-correlation coefficient calculated using DCF. Column (11): time lag calculated using SPEAR method.
Figure 13. Derived CCFs of the observed (triangles) $H\beta$ (upper panels) and $H\gamma$ (bottom panels) time lags from the DCF (left) and ZDCF (middle) methods, and the equivalent probability distribution $P$ from the SPEAR method (right). The solid continuous curves give for comparison the derived CCFs of the corresponding GPR-generated artificial light curve. The vertical lines denote the obtained time lag for the observed (dashed–dotted) and GPR-generated (solid) data.

Figure 14. A comparison of GLS for spectrophotometric light curves. Horizontal lines show the 1% and 5% significance levels for the highest peak determined by 1000 bootstrap samplings. The difference in the Bayesian information criterion ($\Delta BIC$) compares the single harmonic model and the pure noise model. The $x$ axis depicts angular frequencies $\omega = \frac{2\pi}{\text{period}}$. 

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series: (1) a “generalized” Lomb-Scargle periodogram (GLS; Lomb 1976; Scargle 1982), (2) a multitem periodogram routine (MP; Vanderplas et al. 2012; Ivezić et al. 2014), and (3) a Bayesian generalized Lomb-Scargle periodogram (BGLS; Mortier et al. 2015). GLS treats the problem of the mean overestimation by adding a constant offset term to the model. MP treats the problem as if the data have a hidden variability that is more complex than single sinusoidal. BGLS includes both weights and a constant offset in the data.

Figure 14 compares the GLS of our time series. The light curves of the continua at 4200 and 5100 Å and the H$^\beta$ and H$\gamma$ lines have a strong peak corresponding to the period of about 4500 days and is the only statistically significant peak. Periodograms of both H$^\beta$ and H$\gamma$ lines show another two peaks around 1300 days and 780 days ($\omega \in [0.003, 0.005]$), but they are below the 1% and 5% significance levels. The peak of about 780 days (~2 years) can be a consequence of observation conditions. The MP and BGLS techniques give a peak that is also about 4500 days for both the continuum and both line light curves. The periodograms of the fluxes of the photometric curves show three prominent and statistically significant peaks around 4000, 1850, and 1200 days (Figure 14).

Comparing the obtained periods with the observed peaks in the light curve, one can see that the 4000 (photometric) and 4500 (spectroscopic) day periods represent only one cycle period, and it is hard to conclude that we found good evidence for periodic behavior with the approximately 4000-day period. However, the 1200-day period that is associated with the four flare-like events in the photometric light curve represents evidence for a periodic variability in the photometric light curve, as well as in the spectroscopic light curves (1300 days; even it has a small significance level). The period of 1850 days found in the photometric light curve is not present in the spectroscopic light curves. With the current analysis of the variability in the continuum and line fluxes, we cannot find any physical phenomena associated with this period.

The mean sampling period of the continuum and light curves is about 50 days, so it is possible that any shorter period is hidden in the poor data sampling since MP and BGLS could not retrieve them with larger significance.

### 3.2.5. Line Profile Variation

Using the continuum and narrow line subtracted spectra, we constructed the mean and rms line profiles of the broad H$\beta$ and H$\gamma$ components (see Figure 15), which shows that the broad lines have negligible changes in their profiles; that is, during a long period of 24 years, the H$\gamma$ and H$\beta$ line profiles have a strong red asymmetry, and the peaks of both lines are redshifted about 1000 km s$^{-1}$. We measured the FWHM of H$\beta$ of 5610 km s$^{-1}$, which is larger than the FWHM of H$\gamma$ (5060 km s$^{-1}$), while the FWHM of the rms profile of H$\gamma$ (4740 km s$^{-1}$) is only slightly higher than the H$\beta$ one (4520 km s$^{-1}$). In Figure 16 we compare the mean and rms profiles of the H$\gamma$ and H$\beta$ lines. The residuals of the narrow line subtractions have been artificially corrected in the rms profiles for better comparison. As can be seen in Figure 16, the rms profile of H$\beta$ shows smaller changes in the blue wing and in the red part of the line, while the rms of H$\gamma$ shows smaller variability in the far red wing. We compare the mean H$\gamma$ and H$\beta$ profiles (upper panel) and their rms (bottom panel) in Figure 17. It is interesting that the rms profiles seem to be the same, while the mean H$\beta$ has a more extensive red wing than does the mean H$\gamma$. It seems that there is an additional emission in the far wing of the mean H$\beta$, which is clearly seen when the two mean profiles are subtracted (Figure 17, upper panel). We fitted a simple Gaussian through the difference of the mean spectra, which is shifted to 7090 km s$^{-1}$ with an FWHM of 5810 km s$^{-1}$. We measured that the ratio of the red to the blue part of FWHM is 3.8 for the mean H$\beta$ and 3.1 for the mean H$\gamma$, which is confirmed by the observed difference in the asymmetry of the mean profiles.

### 4. DISCUSSION

We have presented and analyzed the photometric and spectral data for QSO E1821+643 obtained from long-term monitoring (2003–2014 for photometry; 1990–2014 for spectroscopy). Here we discuss the results obtained.

#### 4.1. Variation in the Continuum and Broad Lines

The results of the multiwavelength monitoring of E1821+643 in the X-ray, UV, and optical ranges, simultaneously observed for 37 days, were reported in Ulrich et al. (1992). They found that there are no short-term changes in the UV and optical spectra, while in the X-ray there exists a variability on the short-term scale. This result has been confirmed by Kolman et al. (1993); they also found possible changes on the larger timescale in the UV/optical spectra. Here, we explore the
variability of E1821+643 in the 24-year period in the continua at 4200 and 5100 Å and in the broad Hγ and Hβ emission lines. We find significant changes in the line and continuum fluxes during the monitored period. It is interesting that the Hγ line flux has changed about two times (similar to the continua at 4200 and 5100 Å), while the Hβ line showed smaller variations in the line flux (1.4 times). We found that variations of both lines well correlate with variations of the corresponding continuum, but the response of the Hγ line is better than that of the Hβ line. This and the CCF analysis indicate that the emitting region of the Hβ line is distinctly larger than the emitting region of the Hγ line. This indicates a possible stratification in the BLR, showing a smaller Hγ emitting region, which is also observed in a number of AGNs (see Table 13 in Bentz et al. 2010). The BLR photoionization models predict a very similar equivalent distribution as a function of ionization parameter and density (Korista et al. 1997); that is, one cannot expect a significant radial stratification in the broad Balmer line emission regions. However, the possible radial stratification observed between the Hγ and Hβ emission regions in E1821+643 may be caused by optical-depth effects within the Balmer series (Korista & Goad 2004). Korista & Goad (2004) showed that there is a modest increase in responsibility between Hβ and Hγ (see their Table 1). A more detailed investigation of this is outside the scope of this paper.

The variability in the Hβ line segments is present, and it can be seen in Figure 10 that the line core and red wing fluxes are well correlated with the continuum flux at 5100 Å, while a weak correlation is present between the blue wing and continuum fluxes.

4.1.1. Periodicity in the Variability

First we analyzed the photometric light curves and found flare-like events of different amplitudes (0.1–0.5 mag), where the time interval between two consecutive maxima is ~1000 days (see Figure 1 and Table 8). Similar maxima (1–3) are seen in the continuum light curves and possibly, with some delay of ~100 days, in the Hβ and Hγ line light curves and in the broad Hβ component and its line-segment light curves (see Figures 5 and 6). We note that it is difficult to detect these maxima in the observed spectroscopic light curves, given the scatter and sampling of data, however, but these short-timescale fluctuations become clearer in the GPR light curves shown in Figure 12. Since they can indicate periodical or quasi-periodical changes in the flux, we investigated the light curve periodicities and found in all spectral light curves (in the continua and lines) a significant periodicity with a period of 4500 days. In the photometric light curves, there are three periods of 1200, 1850, and 4000 days. However, as we noted above, the periodicity around 4000–4500 days obtained in the spectroscopic and photometric light curves seems to cover only one cycle in our observations and should be confirmed with a longer observation campaign. These periods in the flux

Figure 16. Comparison of the mean and rms spectra of the broad Hβ (upper) and Hγ (bottom).

Figure 17. Comparison of the mean broad Hβ and Hγ profiles (upper) and their rms (bottom). The difference between the Hβ and Hγ mean profiles is also given at the bottom of the upper plot, fitted with a single Gaussian.
variability can indicate some kind of periodical rotation of some structures (in the disk around the SMBH or some cloudy-like gas) around the central SMBH.

4.2. The SMBH Mass and Structure of the BLR

The SMBH mass ($M_{\text{BH}}$) of E1821+643 can be estimated by using the virial theorem (see Peterson et al. 1998; Wandel et al. 1999):

$$M_{\text{GRAV}} = \frac{f \Delta V_{\text{FWHM}} \cdot R_{\text{BLR}}}{G},$$

where $\Delta V_{\text{FWHM}}$ is the orbital velocity at that radius of the BLR, $R_{\text{BLR}}$, and it is estimated from the width of the variable part of the H$\beta$ emission line; $f$ is a factor that depends on the geometry of the BLR and can be taken as $f = 5.5$ (Onken et al. 2004). Taking into account that the dimension of the H$\beta$ BLR is 120 light days (see Table 10) and that the FWHM of the H$\beta$ rms profile is 4520 km s$^{-1}$, we determined that the central SMBH has a mass of $2.6 \times 10^9 M_\odot$, which is in agreement with the estimates given by Kolman et al. (1993); they found that the mass is $3 \times 10^9 M_\odot$.

To discuss the structure of the BLR, we should take into account that the broad line profiles have an unusual shape. As we noted in Section 2, the broad line profiles have a red asymmetry, in which the red wing is two times wider than the blue wing. In addition, the center of the broad H$\beta$ line component is redshifted for $\sim(1000 \pm 250)$ km s$^{-1}$ relative to the peak of the narrow component. In the monitored period, the peak position of the broad H$\beta$ component varies from $\sim700$ to $\sim1600$ km s$^{-1}$ measured as the centroid at 90% of the maximal intensity (see Figure 18). Note here that Landt et al. (2008) reported similar redshifts of 1000–2000 km s$^{-1}$ for the broad components of H$\alpha$, H$\beta$, and several Paschen lines, and here we found that this redshift is changing.

It is interesting that the broad H$\beta$ and H$\gamma$ components have different profiles (see Figure 17), with the second one being narrower, since the H$\beta$ has an extended red wing. Additionally, the CCF analysis shows that the H$\gamma$-emitting region is significantly smaller ($\sim60$ days) than the H$\beta$-emitting region ($\sim120$ days). However, the shapes of the rms of both lines are practically the same (see Figure 17), which indicates a region that is variable and that the emission from this region is mostly contributing to the line core of both lines. The far H$\beta$ wing is emitted from another region that shows a smaller variability (see Figure 17).

Possible shifts of the broad H$\beta$ line peak could be explained with a binary black hole model (Popović 2012) or with an inflowing BLR (Gaskell 2009). It is not safe to conclude that an AGN is a supermassive black hole binary system (SMBB) based only on the broad line profiles since the complex line profiles may also be caused by a complex BLR structure. However, as was noted in Popović (2012), the unusual broad line profiles together with other observational effects, such as quasi-periodical oscillations or indications observed in spectro-polarimetry, could be used for the SMBB detection. The merger hypothesis for E1821+643 has been discussed, and here we consider some results from spectral variability in the frame of this hypothesis.

4.2.1. Recooling SMBH or Supermassive Black Hole Binary System

The high redshifted broad emission lines, in the case of an SMBB system, may be due to the emission from one BLR. In this case, in the center of the circumbinary disk, the system makes a hole, and the secondary SMBH orbits closer to the gas reservoir, and there is only one BLR; that is, the best probability is that the smaller SMBH has only a BLR (see, e.g., Cuadra et al. 2009). In this case, we can expect higher radial velocities, as is seen in the case of broad lines. However, problems with this scenario are that the distances between the two components have to be small (see Table 1 in Popović 2012), and the orbiting period should be shorter than the monitored period, and one can expect high changes in the shift (one can even observe a blueshift in the lines). Though we detected some changes in the redshift of the broad H$\beta$ component (see Figure 18), they do not represent a dramatic change in the broad line shift. This scenario seems to be unlikely.

The second scenario is that the central SMBH and gas are a result of a previous interaction, the so-called recoiling SMBH. This is the case when an SMBH is fueled by the gas from the (former) gaseous (circumbinary) disk that falls into the SMBH (see, e.g., Zanotti et al. 2010). In general, the interaction of the kicked SMBH with the interstellar medium is quite complicated, but simply the reprocessing of the X-ray emission could be responsible for the observed strong emission lines. In that case, the broad lines originate from a standard BLR associated with the recoiling SMBH, and the narrow lines are associated with the host galaxy. The offset in broad emission lines could be detected directly after a high-velocity recoil or at the time of pericentric passages through a gas-rich remnant. The shift of a broad line (with respect to the narrow one) can be expected.
and kick velocities can be on the order of 1000 km s\(^{-1}\); that is, there is a probability that 23% of recoils are larger than 1000 km s\(^{-1}\) (see Lousto et al. 2010). This scenario is in agreement with the observed velocities in the broad lines of E1821+643. However, one should take into account the line-of-sight projection of the velocity, which will always give smaller projected velocities.

Robinson et al. (2010) analyzed the spectropolarimetric observations and showed that the E1821+643 spectrum is only weakly polarized, with an average degree of polarization of 0.21% ± 0.03% at a position angle of 140° ± 5°. The average polarization position angle is approximately perpendicular to the arcsecond-scale radio source. They found that in the polarized flux the broad H\(\alpha\) line shows a strong blue asymmetry and a similar (~1000 km s\(^{-1}\)) blueshift of the peak. Robinson et al. (2010) considered if a possible explanation of their observations could be the scattering of the broad emission lines coming from the active component of an SMBH binary, or the outflowing wind. For an SMBB system, there is a problem with the polarized angle; in this case the scattering geometry would produce a polarization aligned with the direction of the radio jet, which is in contrast to the observations. They support an interpretation of these results in the framework of the hypothesis of a recoiling SMBH. They found that the SMBH is itself moving with a velocity of ~2100 km s\(^{-1}\) relative to the host galaxy. However, to accept the recoiling hypothesis, it seems there should be a very specific coalescence binary configuration.

Additionally, we have to note here that we found some periodicities in the variability of the photometric and spectral data that may also be connected with a binary system. Considering the recoiling scenario, one has a problem in explaining the periodicity detected in the flux variability and also a huge kick-off velocity of the SMBH. However, the extranuclear gas indicates tidal interaction or a merger process in the center of E1821+643 (Fried 1998; Aravena et al. 2011), but it is not clear if the source of the detected gas is a gas-rich companion galaxy that is merging with the quasar’s elliptical host galaxy or if it is a remnant of a previous collision. In fact, the periodicity in the flux variation may be caused by the orbiting of very dense, gas-rich, cloudy-like structures (see Aravena et al. 2011) around a recoiling SMBH. We hope that a detailed investigation of the line profile variability (planned in Paper II) will give more information about the structure of the BLR. Once again we should point out that the observed asymmetry of the broad lines, as well as in the spectrophotometric observations, could be explained by the complex BLR geometry (see Gaskell 2009; Popović 2012).

5. CONCLUSION

We have presented a long-term photometric and spectrophotometric monitoring campaign for E1821+643. The photometric data for the 2003–2014 period (98 nights) are presented in a photometric system close to the Johnson (BV filter) and Cousins (R filter) systems. The spectral data for the 1990–2014 period (127 spectra in H\(\beta\) and 76 spectra in H\(\gamma\)) were unified by the absolute scaling of the observed spectra to the flux of [O\(\text{III}\)]4959+5007 lines and are corrected for aperture effects.

We have constructed the continua, H\(\beta\), and H\(\gamma\) line light curves and investigated the flux variations in the continua and in the total H\(\beta\) and H\(\gamma\) line fluxes, as well as in the broad H\(\beta\) line-segment fluxes. We have cross-correlated the continuum and broad line fluxes and investigated the periodicity in the photometric and spectral flux variation. From our investigation we can outline the following conclusions.

1. The fluxes in the continuum (at 5100 and 4200 Å in the rest frame) and the total H\(\gamma\) line varied about two times, while the total H\(\beta\) line flux varied about 1.4 times (see Table 9) during the monitored period. The amplitude of variability \(F(\text{var})\) is ~19% for the continua and total H\(\gamma\) line, and it is ~7% for the total H\(\beta\) line. This may be caused by different dimensions of the H\(\gamma\)- and H\(\beta\)-emitting regions since our CCF analysis shows that the H\(\gamma\)-emission region is significantly (two times) smaller than the H\(\beta\) one. The CCF of the continuum at 5100 Å and total H\(\beta\) emission-line fluxes shows a lag of ~120 days, while the lag between the continuum at 4200 Å and the total H\(\gamma\) line is ~60 days. The CCF between the continua at 4200 Å and at 5100 Å shows a short time lag of ~2–6 days. This difference in the broad line response delays to the corresponding continuum changes indicates some kind of stratification in the BLR. However, the H\(\beta\) and H\(\gamma\) line fluxes and the H\(\beta\) broad line segments are well correlated with the continuum flux, indicating that the BLR of E1821+643 is primarily photoionized by the central continuum source, and the ionizing continuum is a good extrapolation of the optical continuum.

2. The broad Balmer lines have extremely asymmetric profiles, with the red wing extending to Doppler velocities of at least ~15,000 km s\(^{-1}\) relative to the rest-frame wavelength. The peak of the broad H\(\beta\) component was redshifted relative to the corresponding narrow lines, between ~700 and 1600 km s\(^{-1}\) during the monitored period (see Figure 18). We found that the mean broad H\(\gamma\) and H\(\beta\) profiles are different, with the H\(\beta\) showing an extensive red wing that is broader than the H\(\gamma\) red wing. However, the rms of both lines are practically the same, showing that the line core is the most variable component. We used the estimated BLR dimension and FWHM of the H\(\beta\) rms profile to find the mass of SMBH. We estimate that the SMBH mass in E1821+643 is 2.6 \(\times\) 10\(^{9}\)\(M_\odot\), which is in good agreement with earlier estimations from the Balmer bump.

3. During 2003–2014, the photometric continuum fluxes in the BVR filters showed an almost sinusoidal change (about four maxima or flare-like events), which motivated us to explore whether any periodicity is present in the photometric and spectroscopic light curves. In the photometric light curves we found three periods of variability: 4000, 1850, and 1200 days, while in the spectroscopic variability (in the broad lines and continuum) we found one significant period of 4500 days (see Figure 14). Note here that the periodicity of 4000–4500 days is observed as a cycle periodicity and should be taken with caution. The periodicity of the light curves is probably connected to an orbital motion around the central black hole. In this case, it is hard to explain this fact with the binary black hole hypothesis where only one BLR is present because the shift of the broad lines stays always in the red part of the line. However, there may be a possibility that the periodical variability is
caused by gas-rich, cloudy-like structures that are orbiting around the recoiling black hole.

We are going to investigate the broad line profiles in more detail in Paper II and discuss the changes in the spectral energy distribution and the contribution of the Balmer continuum and changes in the Balmer bump.

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