An X-ray fading, UV brightening QSO at $z \approx 6$

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ABSTRACT

Explaining the existence of super massive black holes (SMBHs) with $M_{BH} \gtrsim 10^8 M_\odot$ at $z \gtrsim 6$ is a persistent challenge to modern astrophysics. Multiwavelength observations of $z \gtrsim 6$ quasi-stellar objects (QSOs) reveal that, on average, their accretion physics is similar to that of their counterparts at lower redshift. However, QSOs showing properties that deviate from the general behavior can provide useful insights into the physical processes responsible for the rapid growth of SMBHs in the early universe. We present X-ray ($XMM$-$\text{Newton}$, 100 ks) follow-up observations of a $z \approx 6$ QSO, J1641+3755, which was found to be remarkably X-ray bright in a 2018 $\text{Chandra}$ dataset. J1641+3755 is not detected in the 2021 $XMM$-$\text{Newton}$ observation, implying that its X-ray flux decreased by a factor $\gtrsim 10$ on a notably short timescale (i.e., $\approx 115$ rest-frame days), making it the $z \approx 4$ QSO with the largest variability amplitude. We also obtained rest-frame ultraviolet (UV) spectroscopic and photometric data with the Large Binocular Telescope (LBT). Surprisingly, comparing our LBT photometry with archival data, we found that J1641+3755 became consistently brighter in the rest-frame UV band from 2003 to 2016, while no strong variation occurred from 2016 to 2021. Its rest-frame UV spectrum is consistent with the average energy distribution (e.g., Shen et al. 2019; Vito et al. 2019), although recently hints of larger blueshifts of high-ionization emission lines in QSOs at lower redshift, in terms of, for example, spectral energy distribution (e.g., Shen et al. 2019; Vito et al. 2019; Yang et al. 2021; Wang et al. 2021a), emission-line ratios (e.g., De Rosa et al. 2014; Mazzucchelli et al. 2017), and radio-loud fraction (e.g., Bañados et al. 2015), although recently hints of larger blueshifts of high-ionization emission lines in $z \gtrsim 6$ QSOs have been reported (e.g., Meyer et al. 2019; Schindler et al. 2020; Vito et al. 2021).

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1 Introduction

The discovery of hundreds of quasi-stellar objects (QSOs) at $z \gtrsim 6$ (i.e., $\lesssim 1$ Gyr after the Big Bang; e.g., Bañados et al. 2016, 2018; Matsuoka et al. 2022; Wang et al. 2021b) poses a serious challenge to our theoretical understanding of how super massive black holes (SMBHs) formed (e.g., Reines & Comastri 2016; Woods et al. 2019). Multiwavelength observations of $z \gtrsim 6$ QSOs provide us with key insights into their accretion physics, helping us understand the fast and efficient phases of SMBH growth in the early universe. Known $z \gtrsim 6$ QSOs are typically found to be luminous ($\lesssim 22 < M_{1450\AA} \lesssim -28$; e.g., Matsuoka et al. 2022) systems powered by already evolved SMBHs ($\log \frac{M_{BH}}{M_\odot} = 8$–10; e.g., Wu et al. 2015; Yang et al. 2021). Their typical physical properties appear similar to those of QSOs at lower redshift, in terms of, for example, spectral energy distribution (e.g., Shen et al. 2019; Vito et al. 2019; Yang et al. 2021; Wang et al. 2021a), emission-line ratios (e.g., De Rosa et al. 2014; Mazzucchelli et al. 2017), and radio-loud fraction (e.g., Bañados et al. 2015), although recently hints of larger blueshifts of high-ionization emission lines in $z \gtrsim 6$ QSOs have been reported (e.g., Meyer et al. 2019; Schindler et al. 2020; Vito et al. 2021).

Quasi-stellar objects are generally known to be variable X-ray sources on timescales of weeks up to years (e.g., Vagnetti et al. 2016). Their typical variability amplitude
rarely exceeds a factor of ≈2 (e.g., Gibson & Brandt 2012; Middei et al. 2017; Timlin et al. 2020), with no evidence of redshift evolution (e.g., Lanzuisi et al. 2014; Shenmer et al. 2017). The amplitude of QSO X-ray variability is known to correlate with the time between different observations (i.e., QSOs are less variable on short timescales; e.g., Paolillo et al. 2017) and to anticorrelate with luminosity (i.e., luminous QSOs are less variable; e.g., Shenmer et al. 2017). In particular, Timlin et al. (2020) demonstrate that extreme variability events (i.e., by factors ≥10) require mechanisms beyond standard accretion physics (see also, e.g., Ni et al. 2020a; Ricci et al. 2020). No systematic study of X-ray variability has been performed on z ≥ 6 QSOs, due to the lack of multi-epoch campaigns and the relatively deep, and thus time-consuming, X-ray observations required to detect high-redshift QOSOs. However, Nanni et al. (2018) report significant flux and spectral variability for the z = 6.31 QSO J1030+0524 (Fan et al. 2001), considering three observation epochs (2002, 2003, and 2017).

As part of an X-ray survey of z > 6 QSOs, in Vito et al. (2019), we present Chandra observations (54.3 ks in total) of the radio-quiet1, luminous (M_{1450} < −25.7; Bahados et al. 2016), optically selected QSO CDFHS J164121+375520 (hereafter J1641+3755) at z = 6.047 (Willott et al. 2007, 2010). This object appears to be powered by a relatively small SMBH (log M_{BH} = 8.4; Willott et al. 2010; Vito et al. 2019) accreting at a super-Eddington rate. The main physical parameters of J1641+3755 are reported in Table 1 (see also Vito et al. 2019).

J1641+3755 was found to be one of the most luminous z > 6 QSOs in the X-ray band (f_{0.5−7 keV} = 1.06^{+0.16}\times10^{-14} erg cm^{-2} s^{-1}, corresponding to an intrinsic luminosity L_{2−10 keV} = 3.3 \times 10^{45} erg s^{-1}; Vito et al. 2019). This finding is surprising considering that J1641+3755 is among the faintest ultraviolet (UV) QSOs known at z > 6 that have been detected in the X-rays (e.g., Vito et al. 2019; Pons et al. 2020; Wang et al. 2021a), making this radio-quiet object an ≈2σ outlier from the α_{ox}−L_{UV} relation2 (α_{ox} = −1.28, Δα_{ox} = 0.35; Vito et al. 2019).

Its X-ray brightness is in contrast with the suppression of X-ray emission usually observed (e.g., Lusso et al. 2012; Luo et al. 2015; Duras et al. 2020; Ni et al. 2022) or expected theoretically (Meier 2012; Jiang et al. 2019, but see also Castelló-Mor et al. 2017) for QSOs accreting at high Eddington ratios. However, basic spectral analysis returned a steep power-law photon index, although with large uncertainties (Γ = 2.4 ± 0.5; Vito et al. 2019), consistent with a super-Eddington accretion rate (e.g., Brightman et al. 2013).

In this paper we present a 100 ks follow-up observation of J1641+3755 with XMM-Newton being performed in February 2021. We found that this QSO has remarkable X-ray variability properties, which led us to perform a Large Binocular Telescope (LBT) Director’s Discretionary Time (DDT) photometric and spectroscopic program. The goal of the LBT observations was to investigate if its rest-frame UV emission varied as well. The paper is structured as follows. In Sect. 2 we report the XMM-Newton and LBT data reduction; in Sect. 3 we present the results of the observations, including the variability in the X-ray and rest-frame UV bands, and the UV spectrum of the QSO, as well as the serendipitous discovery of a possible foreground galaxy structure at z = 0.97; in Sect. 4 we discuss several physical mechanisms that could cause the variability properties of J1641+3755 and in Sect. 5 we summarize our conclusions and discuss the future prospects.

Magnitudes are provided in the AB system. Errors are reported at 68% confidence levels, while limits are given at 90% confidence levels. We refer to the 0.5−2 keV, 2−7 keV, and 0.5−7 keV energy ranges as the soft band (SB), hard band (HB), and full band (FB), respectively. We adopt a flat cosmology with H_0 = 67.7 km s^{-1} and Ω_m = 0.307 (Planck Collaboration XIII 2016).

2. Data reduction and analysis

2.1. XMM-Newton observation of J1641+3755

We observed J1641+3755 with XMM-Newton for 100 ks starting on February 02, 2021, that is to say ≈115 days after the previously mentioned Chandra observations in the QSO rest frame. Table 2 summarizes the observation information, split among the three EPIC cameras.

We proceeded the XMM-Newton observation using SAS v.19.0.4, following standard procedures3. We downloaded the latest release of the Current Calibration Files (CCF), and used the epproc and emproc SAS tasks to calibrate and concatenate the event lists of the EPIC cameras. In order to filter the observations for background-flaring periods, we first produced light curves for EPIC-PN and the two EPIC-MOS cameras in the E = 10−12 keV and E > 10 keV bands, respectively, with the evselect task. Then, we visually inspected the light curves, and chose to filter out periods with count rates >0.45, 0.15, 0.25 cts s^{-1} for the PN, MOS1, MOS2 cameras, resulting in final exposure times of 54, 62, 72 ks, respectively. We checked that reasonably different choices of count-rate thresholds do not impact the results. Then, we used the evselect, exxmap, backscale, rmfgen, and arfgen tasks to create images and exposure maps, as well as to extract spectra, response matrices, and ancillary files.

Figure 1 presents an XMM-Newton full-band image cutout centered on J1641+3755. The three EPIC camera images have been merged with the emosaic task. Visual inspection of the XMM-Newton images and the comparison with the Chandra dataset immediately suggests that J1641+3755 is not detected in the 2021 dataset, and its X-ray emission has varied significantly from the 2018 observation. The latter finding is clearly noticeable considering the emission from a nearby field source, which appeared slightly fainter than J1641+3755 in 2018 and is still clearly visible in the 2021 image.

We analyzed the XMM-Newton photometry of J1641+3755 separately for the three EPIC cameras in the soft, hard, and full bands, following closely the procedure adopted by Vito et al. (2019). We extracted the source counts from a R = 15′′ circular region centered on the optical position of J1641+3755, and the background counts from a nearby R = 30′′ circular region, free of bright sources. The final results are not significantly affected by different choices of the extraction regions. We evaluated the detection significance using the binomial no-source probability P_{0} of Weisskopf et al. (2007) and Broos et al. (2007).

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1 This QSO has R < 10 (Vito et al. 2019), where R = f_{5.5GHz}/f_{4400\lambda} is the radio-loudness parameter, i.e., the ratio of the flux densities at rest-frame 5 GHz and 4400 Å (e.g., Kellermann et al. 1989).

2 The quantity α_{ox} = 0.384 \times (log L_{2−10 keV} − log L_{2500\lambda}) is well known to anticorelate with L_{2500\lambda} (e.g., Steffen et al. 2006; Just et al. 2007; Lusso & Risaliti 2016, 2017). This relation does not significantly change up to z = 7 (e.g., Vito et al. 2019; Wang et al. 2021a). We define Δα_{ox} = α_{ox}(obs) − α_{ox}(exp), where α_{ox}(obs) is the observed value and α_{ox}(exp) is the value expected at a given L_{2500\lambda}.

3 https://www.cosmos.esa.int/web/xmm-newton/download-and-install-sas

4 https://www.cosmos.esa.int/web/xmm-newton/sas-threads
Table 1. Physical properties of J1641+3755.

| ID               | RA          | Dec          | z     | $m_{1450}$Å | $M_{1450}$Å | $\log \left( \frac{L_{\text{bol}}}{L_{\odot}} \right)$ | $\log \left( \frac{M_{\text{BH}}}{M_{\odot}} \right)$ | $\lambda_{\text{Edd}}$ |
|------------------|-------------|--------------|-------|-------------|-------------|---------------------------------------------------|---------------------------------------------------|----------------|
| CFHQSJ164121+375520 | 16:41:21.73 | +37:55:20.15 | 6.047 ± 0.003 | 21.09 | −25.67 | 13.07 | 8.38 | 1.5 |
| "               | 16:41:21.74 | +37:55:20.20 | 6.025 ± 0.002 | 20.92 | −25.84 | 13.13 | "   | 1.7 |

Notes. The first line reports the values used in Vito et al. (2019), and the second line reports the values updated using the 2021 LBT observations (see Sect. 3). Bolometric luminosities were computed from the rest-frame UV luminosity by applying the bolometric correction of Venemans et al. (2016) and Decarli et al. (2018). The SMBH mass was estimated from the Mg II emission line detected in the spectrum presented by Willott et al. (2010).

Table 2. Summary of the X-ray observations of J1641+3755 and net counts.

| Instrument       | ObsID          | Date          | $T_{\text{exp}}$ [ks] | Net counts |
|------------------|----------------|---------------|------------------------|------------|
| 2018 Chandra     |                |               |                        |            |
| ACIS-S           | 20396          | 2018-11-15    | 20.8                   | 39.5±6.6   |
|                  | 21961          | 2018-11-17    | 33.5                   | 47.8±7.3   |
| 2021 XMM-Newton  |                |               |                        |            |
| EPIC-PN          | 0862560101     | 2021-02-02    | 53.9                   | <17.5      |
| EPIC-MOS1        | 0862560101     | 2021-02-02    | 61.9                   | <21.1      |
| EPIC-MOS2        | 0862560101     | 2021-02-02    | 72.4                   | <11.4      |

Notes. Exposure times were filtered for background flaring. The two ACIS-S datasets have been merged and treated as a single observation (see Vito et al. 2019). Therefore, the reported net counts refer to the total exposure.

Fig. 1. Chandra (2018, left) and XMM-Newton (2021, right) full-band images of J1641+3755. The $R = 5''$ solid-line circle is centered on the optical position of the QSO. The dashed circle marks a field source. The dark stripe in the bottom right corner of the XMM-Newton image is an artifact due to a chip gap in the PN camera. Exposure times for the different instruments after removal of periods of high background are also reported.

J1641+3755 is not detected significantly (i.e., we derived $P_B > 0.1$) in any considered energy band by any individual camera.

Upper limits on the net counts were computed from the probability distribution functions (PDFs) of net counts following the method of Weisskopf et al. (2007) and they are reported in Table 2. Following Vito et al. (2019), we derived the PDFs of X-ray flux in the three energy bands from the net count-rate probability distribution function assuming a power-law spectrum with $\Gamma = 2.0^5$, accounting for Galactic absorption (Kalberla et al. 2005) and using the response matrices and PSF-corrected ancillary files extracted at the position of the QSO. Finally, for each energy band, we multiplied the flux PDFs of the three cameras and renormalized the resulting distribution

5 This value is consistent with the average photon index of luminous QSOs (e.g., Shemmer et al. 2006; Nanni et al. 2017), and it is the value used in Vito et al. (2019).
to obtain the average flux PDF. We refer readers to Vito et al. (2019) for a discussion on this procedure. We derived upper limits on the flux in the three energy bands from the averaged PDFs (Table 3).

The rest-frame 2–10 keV band luminosity was computed from the unabsorbed fluxes in the soft band, assuming $\Gamma = 2$. We note that a basic analysis of the 2018 spectrum returned a steeper photon index than the value assumed here ($\Gamma = 2.4 \pm 0.5$). However, the two values are consistent within the uncertainties, and the effect upon the derived flux is minor (see Tables 4 and 7 of Vito et al. 2019). Moreover, in the rest of the paper, we compare the X-ray properties derived from the 2018 and 2021 datasets consistently, assuming $\Gamma = 2$. The comparison between fluxes and luminosities derived from the two observation epochs quantitatively confirms that the X-ray emission of J1641+3755 varied significantly. We discuss this remarkable X-ray variability in Sect. 3.1.

2.2. LBT observation of J1641+3755

Triggered by the detection of the strong X-ray variability of J1641+3755 spanning over ≈115 rest-frame days, in March-May 2021 we carried out an LBT DDT program on this QSO quasi-simultaneously with the XMM-Newton observation (i.e., after 4–12 rest-frame days) to check if the rest-frame UV emission varied as well and to obtain a good quality rest-frame UV spectrum of J1641+3755. We used the Large Binocular Camera (LBC) to obtain imaging in the $r$ and $z$ bands (10 min on source) and both MODS and LUCI to cover the 5000–14000 Å spectral range spectroscopically, including the expected positions of the Ly$\alpha$ and C IV emission lines, for 2 h on source per instrument. Table 4 summarizes the main LBT observation information.

### Table 3. Derived X-ray properties of J1641+3755.

| Epoch | $F_{\text{SB}}$ [$10^{-15}$ erg cm$^{-2}$ s$^{-1}$] | $L_{\gamma}$ [10$^{34}$ erg s$^{-1}$] | $\alpha_{\text{ox}}$ | $\Delta\alpha_{\text{ox}}$ |
|-------|------------------|-----------------|----------------|------------------|
| 2018  | $6.43^{+1.07}_{-0.08}$ | $2.85^{+1.17}_{-0.03}$ | $10.65^{+1.63}_{-1.49}$ | $33.39^{+5.56}_{-5.07}$ | $-1.28^{+0.03}_{-0.03}$ | $0.35^{+0.03}_{-0.03}$ |
| 2021  | $<0.84$          | $<1.71$         | $<1.39$        | $<4.29$          | $<-1.65$        | $<-0.01$        |

Notes. The $\alpha_{\text{ox}}$ and $\Delta\alpha_{\text{ox}}$ values corresponding to the 2018 epoch are those reported in Vito et al. (2019), for reference. Consistent values (i.e., $\alpha_{\text{ox}} = -1.31^{+0.02}_{-0.02}$ and $\Delta\alpha_{\text{ox}} = +0.33^{+0.15}_{-0.02}$) were instead found assuming the updated rest-frame UV photometry and redshift presented in Sects. 3.2 and 3.3.

### Table 4. Summary of the rest-frame UV observations of J1641+3755 with LBT.

| Instrument | Date       | $T_{\exp}$ [h] | $z_{\text{AB}}$ | $J_{\text{AB}}$ |
|------------|------------|----------------|----------------|-----------------|
| LBC        | 2021-03-11 | 0.7            | $21.03 \pm 0.03$ | –               |
| MODS       | 2021-04-03 | 2              | –              | –               |
| LUCI       | 2021-05-04 | 2              | –              | $20.69 \pm 0.05$ |

2.2.2. MODS and LUCI data reductions

Standard MODS and LUCI reductions were carried out by the INAF LBT Spectroscopic Reduction Center in Milan7, where the LBT spectroscopic pipeline was developed (Scodéggi et al. 2005; Gargiulo et al. 2022). Relative flux calibration was obtained using a standard star for MODS and a telluric standard star for LUCI. We performed absolute flux calibration of the final spectra using the simultaneous photometric data obtained with LBT/LBC in the $z$ band and LBT/LUCI in the $J$ band. Finally, we smeared the spectra with a Gaussian function with the standard deviation equal to the instrument wavelength resolutions.

3. Results

3.1. Variable X-ray emission

The X-ray flux declined by factors8 of >6.6 in the soft and full bands, and by a factor of >1.1 in the hard band between the 2018 and 2021 observing epochs (Table 3). The smaller variability limit in the hard band is due to the sensitivity limit of the XMM-Newton observations, which is shallower than in the soft and full band, and the large hard-band flux uncertainties, which are included in the estimate of the variability factor. In fact, the 2018 Chandra observation detected only ≈8 net counts in the hard band, compared to ≈40 and ≈50 net counts in the soft and full bands.

Fig. 2 presents the variability factor of J1641+3755 as a function of the rest-frame time separation between the two observation epochs, compared with other $z > 6$ QSOs observed

7 http://www.isaf-milano.inaf.it/software

8 We conservatively compare the lower boundaries of the 2018 flux intervals reported in Table 3 with the 2021 flux upper limits.
in multiple epochs separated by more than ten rest-frame days (see Appendix A for details on this reference sample). We chose the time-separation threshold as a trade-off between collecting a statistically significant sample, and selecting objects with epoch separations similar to that of J1641+3755. We computed the variability factor as $F_{\text{max}}/F_{\text{min}}$, where $F_{\text{min}}$ and $F_{\text{max}}$ are the minimum and maximum full-band fluxes measured in two consecutive observation epochs, respectively. For consistency, we applied the same analysis to J1641+3755 and the reference QSO sample data.

J1641+3755 clearly shows strong X-ray variability compared to other high-redshift QSOs. In Sect. 4, we discuss some potential scenarios that could explain such a behavior. In addition to J1641, another QSO at $z > 6$, J1030+0524, is found to be significantly variable in the X-ray band, especially between observation epochs 2 and 3, when it varied by a factor of about $\approx 2$ in $\approx 688$ rest-frame days (see Appendix A). We refer readers to Nanni et al. (2018) for a thorough discussion of the variability properties of this object. All of the other QSOs reported in Fig. 2 are consistent with being nonvariable, or at most mildly variable by a factor of $\leq 2$. Recently, Moretti et al. (2021) have reported significant flux (by a factor of $\approx 4$ in the soft band) and a spectral variation in the $z = 6.1$ blazar J0309+2717 on rest-frame timescales of minutes, while in this work we focus on longer timescales.

As a consequence of the flux variability, the X-ray luminosity of J1641+3755 decreased from $L_{2-10\,\text{keV}} \approx 3 \times 10^{45} \, \text{erg s}^{-1}$ to $L_{2-10\,\text{keV}} \leq 4 \times 10^{44} \, \text{erg s}^{-1}$ (Table 3 and Fig. 3). The X-ray and bolometric luminosities of J1641+3755 in the two epochs are compared with those of other optically selected QSOs, and with the best-fitting relation of Duras et al. (2020) in Fig. 3. J1641+3755 was a significantly brighter X-ray source than QSOs with a similar bolometric luminosity in 2018, while its X-ray luminosity decreased to an X-ray normal, and possibly even weak, state in 2021.

Timlin et al. (2020) show that only $\approx 1\%$ of radio-quiet QSOs at all redshifts experience variability as dramatic as that seen from J1641, and this typically happens over longer timescales than what is probed for J1641. Moreover, the few extreme variability events known in QSOs can be linked with accretion physics beyond simple fluctuations of the accretion flow (see also, e.g., Ricci et al. 2020). For instance, recently Ni et al. (2020a) have presented extreme X-ray variability from a $z = 1.9$ weak-line QSO, which they interpret as an occultation event due to a thick inner accretion disk. Liu et al. (2019, 2021) report that a fraction of $\approx 15\%$ of super-Eddington accreting QSOs, as J1641+3755 is (Table 1), are variable in the X-ray band by factors $>10$. Since all such QSOs varied between X-ray normal and weak states, the authors propose that small-scale absorption can account for the flux variation. This interpretation does not explain the X-ray bright state of J1641+3755 in 2018 (see Sect. 4). Before J1641+3755, the most extreme X-ray variation in a $z > 4$ radio-quiet QSO was a factor of $4.5^{+1.3}_{-1.7}$ in 74 rest-frame days for an object at $z = 5.4$ (Shemmer et al. 2005).

### 3.2. Variable rest-frame UV emission

From the 2021 LBT/LBC observations, we derived an AB magnitude $m_{\text{AB, J1641+3755}} = 21.03 \pm 0.03$ for J1641+3755. In Fig. 4 we compare this value with the magnitudes derived from previous datasets. In particular, J1641+3755 is covered by the Canada France Hawaii Telescope (CFHT) Legacy Survey (CFHTLS), which was used to select it as a high-redshift
QSO candidate originally (Willott et al. 2007). Moreover, J1641+3755 was detected by the PanSTARRS PS1 survey (e.g., Chambers et al. 2016) and the Mayall z-band Legacy Survey (MzLS; e.g., Dey et al. 2019). We downloaded the calibrated images and performed photometry with SExtractor using a consistent approach among the various datasets as described in Sect. 2.2.1. We calibrated the magnitudes using the public catalogs of the surveys. The observation dates reported in Fig. 4 were taken directly from the headers of the files, except for PanSTARRS PS1, for which it is the median value of the individual images covering J1641+3755.

In order to correct for the different z-band filters used to measure the QSO magnitudes in the various datasets, and thus be able to compare them fairly, we used the observed spectrum of J1641, which is presented in Sect. 3.3, to compute the offsets between the different filters. In particular, we convolved the spectrum with the z-band filters, obtaining synthetic magnitudes. The difference between the magnitude retrieved with the LBC filter and those obtained with the filters of the remaining facilities provided us with correction factors which we applied to the magnitudes measured from the CFHT, PanSTARRS, and MzLS datasets. The resulting magnitudes are in the LBC system, and they are reported in Fig. 4. This approach assumes that the spectral shape of J1641 has not varied significantly over the time baseline covered by the several datasets, as we discuss in Sect. 3.3. The final magnitudes of J1641+3755 corresponding to the LBC z-band filter are \( z_{\text{SDSS}} = 21.24 \pm 0.06 \), \( z_{\text{SDSS}} = 21.09 \pm 0.12 \), and \( z_{\text{SDSS}} = 20.99 \pm 0.09 \) for the CFHT, PanSTARRS, and MzLS datasets, respectively.

Using these four independent measurements, we conclude that J1641+3755 has increased its rest-frame UV flux from 2003 to 2016 (i.e., over \( \approx 2 \) rest-frame years) by \( \approx 0.25 \) mag (Fig. 4), while no significant variation is found afterward. This behavior is the opposite of what we derived for the X-ray emission, although we note that the observation epochs before 2021 are very different among rest-frame UV and X-ray datasets. In particular, no rest-frame UV observation is available in 2018 (see solid vertical line in Fig. 4), when we detected bright X-ray emission from this QSO. Future observations of J1641 will reveal if its rest-frame UV emission remains constant or shows additional variability.

### 3.3. Rest-frame UV spectrum

Figure 5 presents the rest-frame UV spectrum of J1641+3755 obtained combining the LBT/MODS and LBT/LUCI observations. We measured a systemic redshift of \( z = 6.025 \pm 0.002 \) based on the Si IV 1400 Å and C III\( \] 1909 Å emission lines, which is slightly lower than the Willott et al. (2010) value of \( z = 6.047 \pm 0.003 \) based on the Mg II 2798 Å emission line.

The spectrum of J1641+3755 is broadly consistent with the composite spectrum of \( z > 5.7 \) QSOs of Shen et al. (2019). The spectral region at \( \lambda > 1.3 \mu m \) is at the red limit of the LBT/LUCI coverage, where the sensitivity drops and flux calibration becomes more uncertain. At those wavelengths, the difference between the J1641+3755 spectrum and the composite spectrum is larger.

Several narrow absorption lines are visible in the spectrum (see Table 5). Some of them are identified with atomic transitions consistent with a \( z = 5.67 \) intervening system and are marked with red vertical ticks in Fig. 5, while others are currently unidentified (gray vertical ticks). Fig. 6 zooms into the spectral ranges where the absorption features are detected, for a better visualization. The unidentified features may be due to absorbing material in the QSO rest frame, or one or more additional foreground systems. The emission “spikes” at wavelengths shorter than the Ly\( \alpha \) emission line are probably due to the QSO radiation partially passing through the Ly\( \alpha \) forest when it encounters regions along the line of sight with an increased ionized hydrogen fraction, which is possibly related to the presence of intervening ionizing sources, such as foreground galaxies.

Assuming rest-frame continuum emission in the form of a simple power-law \( F_\lambda \propto (\lambda/2500 \text{ Å})^{-\alpha} \), we fitted the wavelength range 11 730–12 645 Å, corresponding to rest-frame 1670–1800 Å, to retrieve the best-fitting UV spectral slope with a \( \chi^2 \) minimization method. We note that usually the UV spectral slope is fitted over several more wavelength intervals (e.g., Mazzucchelli et al. 2017), which are, however, affected by absorption features in the J1641+3755 spectrum, or out of the available spectroscopic coverage. Following Shen et al. (2019) and Yang et al. (2021), for example, we used a Monte Carlo
approach to estimate the uncertainties: we generated a set of 100 mock spectra by perturbing the original spectrum at each pixel with random Gaussian noise with the standard deviation being set equal to the spectral uncertainty at that pixel. Then, we estimated the uncertainties on the parameter values as the 16% and 84% percentile of the final best-fitting value distribution. We derived a best-fitting $\alpha_J = -0.91^{+0.36}_{-0.11}$ (dotted purple line in Fig. 5). Due to the limited “leverage” provided by the fitted wavelength range, the uncertainties are large and the best-fitting value itself is quite sensitive to the exact wavelength interval used in the fitting.

We also fit the C IV emission line, assuming a more complex model that simultaneously includes, in addition to the intrinsic continuum, the Balmer pseudo-continuum modeled as in Schindler et al. (2020), the iron pseudo-continuum template of Vestergaard & Wilkes (2001), and a Gaussian function for the C IV line (Fig. 7). To be consistent with previous literature works (e.g., Mazzucchelli et al. 2017; Schindler et al. 2020; Vito et al. 2021), we convolved the iron pseudo-continuum model with a Gaussian function with the width being equal to that of the Mg II emission line. Since that line is not covered by our spectrum, we assumed the width reported by Willett et al. (2010). We performed the fit in the rest-frame wavelength ranges 1480–1590 Å and 1670–1800 Å. We obtained a best-fitting $\alpha_J = -1.40^{+0.67}_{-0.52}$, while the C IV emission line is centered at $\lambda = 10843^{+3}_{-2}$ Å (i.e., $z_{CIV} = 6.000 \pm 0.002$), corresponding to a blueshift of $\approx -1100$ km s$^{-1}$ from the systemic redshift, with $FWHM = 4453^{+416}_{-262}$ km s$^{-1}$ and rest-frame equivalent width $REW = 17^{+1}_{-5}$ Å. These values are consistent with typical measurements reported for $z \gtrsim 6$ QSOs (e.g., Shen et al. 2019; Schindler et al. 2020; Yang et al. 2021), and with the prescription of Dix et al. (2020), which links the blueshift, FWHM, and equivalent width (EW) of the C IV emission line with the UV luminosity of a QSO.

In Fig. 8, we compare the 2021 LBT spectrum of J1641+3755 with a 2007 Keck/ESI spectrum covering the 4000–9300 Å range, which was presented by Willett et al. (2007) and Eilers et al. (2018), and normalized at rest-frame 9000 Å. The two spectra are broadly consistent in terms of the spectral shape, the Ly$\alpha$ and N V emission-line complex, and the presence of several narrow absorption features at high redshift.
Table 5. Narrow absorption features detected in the J1641+3755 rest-frame UV spectrum.

| \( \lambda \) [Å] | Transition | \( z \) |
|-----------------|------------|-------|
| 8504            | ...        | ...   |
| 8517            | ...        | ...   |
| 8533            | ...        | ...   |
| 8606            | ...        | ...   |
| 8626            | ...        | ...   |
| 8689            | O I 1302.2 Å | 5.672 |
| 8702            | Si II 1304.4 Å | 5.671 |
| 8906            | C II 1334.5 Å | 5.674 |
| 9304            | Si IV 1393.8 Å | 5.675 |
| 9373            | Si IV 1402.8 Å | 5.682 |
| 9636            | ...        | ...   |
| 10 044          | ...        | ...   |
| 10 190          | Si II 1526.7 Å | 5.674 |
| 10 229          | Si II 1534.4 Å | 5.667 |
| 10 347          | C IV 1548.2 Å | 5.683 |
| 10 376          | C IV 1550.8 Å | 5.691 |
| 10 666          | ...        | ...   |
| 10 681          | ...        | ...   |
| 10 727          | Fe II 1608.5 Å | 5.669 |
| 10 750          | Fe II 1608.5 Å | 5.683 |
| 11 150          | Al II 1670.8 Å | 5.673 |
| 12 545          | ...        | ...   |
| 12 699          | Fe II 1901.8 Å | 5.678 |
| 12 838          | Fe III 1926 Å | 5.664 |

Notes. The identified transitions are consistent with an intervening system at \( z = 5.67 \) (red vertical ticks in Fig. 5).

8500–9000 Å, suggesting that the rest-frame UV variability discussed in Sect. 3.2 is not due to a variation in the spectral shape, at least in this relatively narrow wavelength range.

4. Discussion

4.1. Possible causes for the variability of J1641+3755

Any physical interpretation of the variability properties of J1641+3755 should address both the fading of the X-ray emission over a rest-frame period of 115 days (Sect. 3.1), corresponding to a light-crossing distance \( d < c t \approx 0.1 \) pc, which is comparable to the size of a QSO accretion disk, and the QSO brightening in the rest-frame UV band (Sect. 3.2). Ideally, any interpretation should explain the fact that in 2018, J1641+3755 was a \( 2\sigma \) positive outlier from the \( L_X - L_{bol} \) and \( \alpha_{XV} - L_{XV} \) relations (Vito et al. 2019; see, e.g., Fig. 3)\(^1\). However, there is an additional complication due to the non simultaneity of the rest-frame UV and X-ray observations (see Table 2 and Fig. 4).

The variability of J1641+3755 can be a result of intrinsic or extrinsic physical effects. Here we discuss some possible explanations involving intrinsic mechanisms. According to standard accretion physics, a drop in the SMBH accretion rate\(^1\) should have produced a decrease in the rest-frame UV emission, in addition to the drop in the X-ray flux (e.g., LaMassa et al. 2015). However, our LBC observations reveal that between 2016 and 2021, the QSO did not vary its rest-frame UV magnitude significantly, and it was brighter than in previous epochs. This tension may be due to the nonsimultaneity of the X-ray and UV observations epochs before 2021, as the bright X-ray state in 2018 could correspond to a bright UV state, which, however, might not have been detected due to the lack of simultaneous UV observations. Alternatively, the 2018 X-ray epoch could correspond to a strong and short local maximum of a long-term fading X-ray light curve, as QSO variability timescales are generally shorter in the X-rays than in the UV band. However, as discussed in Sect. 3.1, such a strong X-ray variability event on short timescales is remarkably rare for a luminous QSO.

On the other hand, some models predict a brightening of the rest-frame UV emission and a suppression of X-ray emission for increasing accretion rates (e.g., Giustini & Proga 2019). This behavior is usually associated with the launch of strong and fast nuclear winds, for which, however, we do not find definitive evidence in Fig. 5.

Finally, intervening heavy obscuration on spatial scales comparable with the inner accretion disk could completely screen the X-ray emission, leaving the rest-frame UV unaffected. For instance, models of super-Eddington accretion predict the presence of a geometrically thick inner disk (e.g., Wang et al. 2014; Jiang et al. 2019). In this case, a change in the disk thickness (e.g., due to disk rotation or variation in the accretion rate) can produce the X-ray variability observed for J1641+3755, similarly to the event discussed by Ni et al. (2020a, 2022), while an increase in the accretion rate would account for the UV brightening.

All of the aforementioned possibilities describe the X-ray variability of J1641+3755 well, but they rely on a secondary effect to explain why its X-ray luminosity in 2018 was significantly higher than the expectation from the \( L_X - L_{bol} \) relation. In particular, they require an undetected bright UV state in 2018 due to the lack of UV observations, or that the 2018 X-ray emission was produced by an extreme and rare burst.

Possible extrinsic effects account, more easily, for the J1641+3755 variability properties and its apparent bright X-ray state in 2018. For instance, J1641+3755 may be an intrinsically low-luminosity QSO, whose emission is boosted by gravitational lensing due to a foreground object or structure, similarly to the first lensed \( z > 6 \) QSO recently discovered by Fan et al. (2019). A modest magnification factor (\( \approx 5-10 \)) would bring the 2018 luminosity back to the expected relation between \( L_X \) and \( L_{bol} \). In this context, the strong X-ray flux variation can be intrinsic, as QSO variability amplitude is generally found to increase for decreasing luminosity (e.g., Shemmer et al. 2017), due to a small-scale obscuration event in 2021 (e.g., Liu et al. 2019; Ni et al. 2020b), or due to microlensing effects. In fact, microlensing due to the stars in a lens galaxy aligned with a QSO can produce observed flux variability in addition to intrinsic variability (e.g., Chen et al. 2012; MacLeod et al. 2015), variation time. However, for BHs accreting at super-Eddington rates, as is likely J1641+3755, the accretion disk might be geometrically thick (e.g., Wang et al. 2014; Jiang et al. 2019). In this case, \( t_{\text{vis}} \) decreases sharply below the observed variability timescale (e.g., Czerny 2006; Fabrika et al. 2021). Therefore, we cannot discard a variation in the accretion rate as the cause for the observed variability of J1641+3755 using timescale arguments.

\(^{18}\) We note that consistent results are obtained regardless of which UV epoch is chosen to compute \( L_{bol} \) and \( \alpha_{XV} \); see Table 1 and Table 3.

\(^{19}\) We note that the viscous timescale \( t_{\text{vis}} \) (i.e., the typical timescale on which the accretion rate varies) of a standard geometrically thin accretion disk for \( M_{\text{BH}} \approx 10^8 M_\odot \) is longer than the observed \( \approx 115 \) day
Flux [10^{-17} erg cm^{-2} s^{-1} Å^{-1}]

Fig. 6. Zooms into the portions of the J1641 spectrum where narrow absorption lines are detected (see Sect. 3.3 and Table 5). Transitions identified with an intervening system at \( z \approx 5.67 \) are marked with vertical red lines, while unidentified lines are marked with vertical gray lines. Other apparent absorption features (e.g., in the second and third panels of the first row) are consistent with sky-line residuals.

This finding suggests that enhanced variability may be a characteristic property of high-redshift QSOs, which is perhaps linked with the physics of the fast accretion rate required to grow to \( 10^9 M_\odot \) in a few hundred million years. In fact, the incidence of extreme variability events has been found to correlate with the Eddington ratio (e.g., Miniutti et al. 2012; Liu et al. 2019, 2021; Ni et al. 2020a, 2022), and the accretion rates of known \( z \approx 6 \) QSOs are typically close to the Eddington limit. Multi-epoch X-ray observations of high-redshift QSOs with current (e.g., the XMM-Newton Multi-Year Heritage Programme \textit{Hyperion}; PI: L. Zappacosta) and future (e.g., Marchesi et al. 2020) facilities are required to confirm this hypothesis since, for instance, QSOs at \( z \approx 4 \) do not obviously present such an enhancement compared with the general population at lower redshift (e.g., Lanzuisi et al. 2014; Shemmer et al. 2017).

4.2. Possible enhanced X-ray variability in high-redshift QSOs

Out of ten QSOs at \( z > 6 \) covered with multi-epoch X-ray data (set to \( \Delta t > 10 \) rest-frame days), at least two (J1641+3755 and J1030+0524; i.e., \( 20\% \)) present significant X-ray variability (i.e., by a factor of \( \geq 3 \); see Fig. 2). The incidence of X-ray variable QSOs at high redshift increases if radio-loud objects (i.e., J0309+2717 and J1429+5447) are excluded. For comparison, Timlin et al. (2020, see their Fig. 8) found that a variability amplitude by a factor of \( \geq 3 \) is detected for \( <10\% \) of the general radio-quiet QSO population. Such a fraction decreases if QSOs, with observation epochs separated by timescales similar to that of J1641+3755 or with similar luminosities to J1641+3755, are considered (Figs. 7 and 8 of Timlin et al. 2020). In fact, \( z > 6 \) QSOs are typically luminous systems, which at later cosmic times are usually found to be less variable than low-luminosity objects (e.g., Shemmer et al. 2017; Thomas et al. 2021).

5. Conclusions and future prospects

We have presented quasi-simultaneous X-ray and rest-frame UV observations of the \( z = 6.025 \) QSO J1641, which was already...
observed in both bands in previous epochs. Here, we summarize the main conclusions:

- We did not detect J1641+3755 in a 100 ks XMM-Newton observation performed in 2021. The comparison with a 2018 (i.e., 115 rest-frame days before) Chandra observation, which detected J1641+3755 as a luminous QSO, reveals that the X-ray emission from this object dropped by a factor $\approx 7$, which is the most extreme one witnessed in a $z > 4$ QSO (Shemmer et al. 2005). Timlin et al. (2020) show that only $\approx 1\%$ of the general QSO population has been found to experience such a strong variation, and typically on much longer timescales.

- Two QSOs (J1641+3755 and J1030+0524) out of the ten QSOs at $z > 6$ observed in the X-ray band in multiple epochs separated by more than ten rest-frame days and detected in at least one epoch are found to be strongly variable (i.e., by a factor $>3$). This fraction is higher than that observed at lower redshift (i.e., $<10\%$), although its statistical significance is poor due to the limited sample size. Enhanced variability can be a characteristic property of high-redshift QSOs, possibly linked with the physics of fast accretion required to form $\geq 10^9 M_\odot$ SMBHs at $z > 6$. Future X-ray observations of high-redshift QSOs will confirm this hypothesis.

- A four-epoch rest-frame UV light curve of J1641+3755 revealed that it became brighter by $\approx 0.25$ mag from 2003 to 2016, whereas it did not vary significantly afterward. This behavior is opposite to what we found for the X-ray emission. However, observations in the two bands before 2021 were performed nonsimultaneously, hindering a clear physical interpretation.

- The rest-frame UV continuum and emission-line properties of J1641+3755 are consistent with what is found for the general population of high-redshift QSOs. However, several narrow absorption lines are detected as well, and a number of them are consistent with transitions due to an intervening population of high-redshift QSOs. However, several narrow absorption lines are detected as well, and a number of them are consistent with transitions due to an intervening system at $z = 5.67$.

- We have discussed a number of possible physical explanations for the remarkable variability properties of J1641, including intrinsic and extrinsic causes. The former causes include a variation in the accretion rate, possibly coupled with absorption due to outflowing material or a thick accretion disk. Among the latter is gravitational lensing, which would imply that J1641+3755 is intrinsically less luminous than what appears, alleviating the tension between its luminosity and strong variability. The bright X-ray emission in 2018, when J1641+3755 was a $2\sigma$ outlier from known relations between $L_X$ and $L_{UV}$, is the most difficult result to explain with these scenarios. A possibility is that it was due to a foreground event (e.g., a tidal disruption event) not physically associated with J1641.

Monitoring observations of J1641+3755 will allow us to follow and constrain its variability behavior better. In particular, we have recently secured a multicycle Chandra program to follow-up on J1641+3755 and test if it returns to a bright X-ray state, or to place tighter constraints on its current X-ray luminosity. Additional LBT/LBC observations will confirm the UV brightening of J1641+3755. An important aspect is to obtain quasi-simultaneous X-ray and rest-frame UV data to check if the UV emission indeed follows the opposite trend as the X-ray variability, or if that finding was due to the different time base-lines probed in the two bands in this work. The results will help the physical interpretation of the variability properties of J1641+3755, considering the several possible causes we have discussed.

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Appendix A: Sample of \( z > 6 \) QSOs with multiple-epoch X-ray observations

We collected a sample of ten QSOs at \( z > 6 \) covered with X-ray observations in multiple epochs separated by more than ten rest-frame days (Tab. A.1). All of these QSOs are not bright radio sources, except for the radio-loud QSOs J0309+2717 and J1429+5447. We grouped observations performed within ten rest-frame days in an individual epoch, with the exception of J1030+0524. This QSO was observed in 2017 with a Chandra Large Program (Nanni et al. 2018) consisting of ten pointings from January to May 2017 (i.e., more than ten rest-frame days). Since it is not straightforward to divide such pointings into multiple epochs, and given the lack of variability among them as reported by Nanni et al. (2018), we considered all of them as a single epoch for simplicity (i.e., epoch 3 in Tab. A).

For most QSOs, we reduced the X-ray data and derived the full-band flux in each epoch in a consistent way using the procedure described in Vito et al. (2019) and Sect. 2.1 for Chandra and XMM-Newton datasets. The flux of J1429+5447, instead, was extrapolated from the value reported in Medvedev et al. (2020) in the 2 – 4 keV band, as eROSITA data are not publicly available. Moreover, the flux of the first epoch of J0309+2717 was derived assuming \( \Gamma \approx 1.6 \), instead of \( \Gamma \approx 2.0 \) which was used for the other QSOs in the sample. We refer readers to Moretti et al. (2021) for an in-depth investigation of the X-ray spectral shape of this QSO. In general, we note that the errors on the derived flux of the QSOs in the sample are dominated by the uncertainties on the net-count rates rather than the assumed photon index value.

We computed the variability factor between two consecutive epochs as \( F_1/F_2 \) if \( F_1 > F_2 \), or \( F_2/F_1 \) if \( F_2 > F_1 \). Errors on the variability factor account for the flux uncertainties in both epochs. We note that in the cases of QSOs observed in three epochs (i.e., J0309+2717 and J1030+0524), the variability factors reported in the third epoch were computed with respect to the fluxes in the second epoch.
Table A.1. Main information of the reference sample used in Fig. 2.

| ID       | z   | Ref. (e) | Epoch | Telescope | ObsID (X-ray) | $T_{exp}$ (ks) | $A_{p}$ (Days) | Flux (0.5–7 keV) $10^{-15}$ erg cm$^{-2}$ s$^{-1}$ | Var. Fact. |
|----------|-----|----------|-------|-----------|---------------|----------------|----------------|-----------------------------------------------|------------|
| J0100+2802 | 6.3258 | 1 | 1 | Chandra | 17087 | 10 | 15 | 0.0 | 8.5$^{+2.4}_{-2}$ |
|          |      |          |       | XMM-Newton | 0709180701 | 11 | 45/61/60 | 35.1 | 12.14$^{+0.3}_{-0.4}$ |
| J0224+4711 | 6.5223 | 2 | 1 | Chandra | 20418 | 2 | 18 | 0.0 | 11.39$^{+2}_{-2}$ |
|          |      |          |       | XMM-Newton | 0824400301 | 12 | 16/31/31 | 10.6 | 9.6$^{+1.5}_{-2.3}$ |
| J036+03 | 6.541 | 3 | 1 | Chandra | 0803161501 | 12 | 16/19/19 | 0.0 | 3.6$^{+1.2}_{-1}$ |
|          |      |          |       | XMM-Newton | 20390 | 13 | 26 | 35.3 | 2.4$^{+1.2}_{-1}$ |
| J039+2717 | 6.10 | 4 | 1 | Swift | 00012068001 | 4 | 19 | 0.0 | 24.5$^{+0.5}_{-0.0}$ |

Notes. (1) QSO ID; (2) redshift; (3) reference for the redshift; (4) X-ray observation epoch; (5) telescope used for the X-ray observation; (6) observation ID; and (7) reference for the X-ray observation. We stress that we recomputed the fluxes as described in Appendix A. (8) Total exposure time of the observation epoch. Exposure times were filtered for background flaring and are reported separately for the EPIC PN, MOS1, and MOS2 cameras for XMM-Newton observations. (9) Time separations between epochs, in units of rest-frame days from the first observation epoch. We used the starting time of the observation, or the average of the starting times of the observations in the case of multiple pointings, as the time of one epoch. (10) Flux in the 0.5–7 keV band; and (11) X-ray variability factor, as defined in Sect. 3.1.

References. 1: Wang et al. (2016). 2: Wang et al. (2021a). 3: Mazzucchelli et al. (2017). 4: Belladitta et al. (2020). 5: Kurk et al. (2007). 6: Venemans et al. (2012). 7: Decarli et al. (2018). 8: Wang et al. (2011). 9: this work. 10: Ai et al. (2016). 11: Ai et al. (2017). 12: Pons et al. (2020). 13: Vito et al. (2019). 14: Ighina et al. (2022). 15: Brandt et al. (2002). 16: Farrar et al. (2004). 17: Nanni et al. (2018). 18: Moretti et al. (2014). 19: Schwartz & Virani (2004). 20: Medvedev et al. (2020). 21: Medvedev & Titarchuk (2021). 22: Connor et al. (2019). 23: Webb et al. (2020).