X-ray softening in the new X-ray transient XTE J1719–291 during its 2008 outburst decay

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ABSTRACT
The X-ray transient XTE J1719–291 was discovered with Rossi X-ray Timing Explorer/Proportional Counter Array (RXTE/PCA) during its outburst in 2008 March, which lasted at least 46 d. Its 2–10 keV peak luminosity is \(7 \times 10^{35} \text{ erg s}^{-1}\) assuming a distance of 8 kpc, which classifies the system as a very faint X-ray transient. The outburst was monitored with Swift, RXTE, Chandra and XMM–Newton. We analysed the X-ray spectral evolution during the outburst. We fitted the overall data with a simple power-law model corrected for absorption and found that the spectrum softened with decreasing luminosity. However, the XMM–Newton spectrum cannot be fitted with a simple one-component model, but it can be fitted with a thermal component (blackbody or disc blackbody) plus a power-law model affected by absorption. Therefore, the softening of the X-ray spectrum with decreasing X-ray luminosity might be due to a change in photon index or alternatively it might be due to a change in the properties of the soft component. Assuming that the system is an X-ray binary, we estimated a long-term time-averaged mass accretion rate of \((\dot{M}_{\text{long}}) \sim 7.7 \times 10^{-13} \text{ M}_\odot \text{ yr}^{-1}\) for a neutron star as a compact object and \((\dot{M}_{\text{long}}) \sim 3.7 \times 10^{-13} \text{ M}_\odot \text{ yr}^{-1}\) in the case of a black hole. Although no conclusive evidence is available about the nature of the accretor, based on the X-ray/optical luminosity ratio we tentatively suggest that a neutron star is present in this system.

Key words: accretion, accretion discs – stars: individual: XTE J1719–291 – X-rays: binaries.

1 INTRODUCTION
X-ray transients spend most of the time in a dim quiescent state, with an X-ray luminosity of \(10^{33}–10^{34} \text{ erg s}^{-1}\). It is mostly during outbursts that these systems are discovered, when the luminosity increases by more than two orders of magnitude. The nature of these X-ray transients is varied. Many of them are compact objects [black holes (BHs) or neutron stars (NSs)] accreting matter from a companion star. In these systems, the outbursts are attributed to a strong increase in the accretion rate on to the compact object due to a hydrogen ionization instability in the accretion disc (Lasota 2001).

The peak luminosity reached during these accretion outbursts \(L_X^{\text{peak}}\) covers a wide range, from \(10^{34}–10^{39} \text{ erg s}^{-1}\). Depending on this luminosity, X-ray transients can be classified as bright \((L_X^{\text{peak}} \sim 10^{37}–10^{39})\), faint \((L_X^{\text{peak}} \sim 10^{34}–10^{36})\) or very faint \((L_X^{\text{peak}} \sim 10^{34}–10^{36};\) see Wijnands et al. 2006). This classification is not strict since hybrid systems do exist which exhibit large variations in their peak \(L_X\) from the outburst to outburst (e.g. SAX J1747.0–2953; Wijnands, Miller & Wang 2002; Werner et al. 2004).

Very faint X-ray transients (VFXTs) have been discovered in the last decade thanks to the improvement in sensitivity of X-ray instruments. Currently, several tens of VFXTs are known, but despite the reasonable number of sources detected, only very few of them have been studied in detail during outbursts. Hence, the characteristics of these peculiar sources as well as their nature are still poorly understood. Some of them are NSs accreting from, most likely, low-mass stars, since these systems have shown Type-I bursts (e.g. Cornelisse et al. 2002; Chelovekov & Grebenev 2007; Del Santo et al. 2007; Degenaar & Wijnands 2009). Classical novae are a possible class of these very faint transients too. Mukai, Orio & Della Valle (2008) have argued that systems may be a small part of the X-ray transients’ population in the Galactic Centre, since they can reach peak luminosities in the \(10^{34}–10^{35} \text{ erg s}^{-1}\) range through nuclear fusion of the matter accreted on the white dwarf’s

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surface. Another possibility are the symbiotic X-ray binaries, a small subclass of low-mass X-ray binaries (LMXBs) in which the compact primary, most likely an NS, is accreting matter from the wind of an M-type giant companion. Only a few such symbiotic X-ray binaries have been identified so far (e.g. Masetti et al. 2007). Also several strongly magnetized NSs ($B \sim 10^{14} - 10^{15}$ G, magnetars) have shown the X-ray outbursts with peak luminosities of $\sim 10^{38}$ erg s$^{-1}$ (e.g. Ibrahim et al. 2004; Muno et al. 2007). They are the only known non-accreting systems that can exhibit VFXT outbursts. The cause of these transient outbursts is not fully understood, but likely it is related to a decay in the strong magnetic field of the NS (Ibrahim et al. 2004). It is also possible that a fraction of these underluminous transients are high-mass X-ray binaries (HMXBs), i.e. compact objects accreting from a circumstellar disc or the strong stellar wind of a star with a mass higher than 10$M_{\odot}$ (e.g. Okazaki & Negueruela 2001).

The low luminosities of VFXTs in which a compact object accretes from a low-mass donor in combination with duty cycles of $\leq$10 per cent (as is common for the brighter X-ray transients) imply that the mean accretion rates in these systems are very low (e.g. Degenaar & Wijnands 2009). Therefore, such VFXTs provide us with new regimes to study accretion on to compact objects. For example, by studying the outburst’s properties of the systems that harbour an NS (e.g. displaying X-ray pulsations or bursts) new ways of studying ultra-dense matter can be performed (Wijnands 2008). Moreover, VFXTs yield new inputs for the outburst and evolution models that were developed to explain the bright systems, but are not able to account for all the VFXT manifestations (e.g. King & Wijnands 2006).

In this work, we present an extensive X-ray analysis of XTE J1719–291, which was discovered with Rossi X-ray Timing Explorer/Proportional Counter Array (RXTE/PCA) bulge scans on 2008 March 21 (Markwardt & Swank 2008). Its outburst was monitored with Swift, which initially showed an X-ray flux decrease (Degenaar et al. 2008a; Markwardt & Swank 2008), but then re-brightened (Degenaar, Altamirano & Wijnands 2008b). A duration of 46 d elapsed between the source’s discovery and the time when it was no longer detectable (Degenaar & Wijnands 2008). The most accurate position was obtained with Chandra, $\alpha = 17^h 19^m 17.18^{s}$, $\delta = -29^\circ 04' 10.0''$ with an uncertainty of 0.2 arcsec ($\sigma$2000, 90 per cent confidence; Greiner, Sala & Kruehler 2008). At this position a strong background flare. We exclude the data where the count rate exceeded 1 and 0.5 counts s$^{-1}$ for the pn and MOS data, respectively, which results in a total live time of 17 ks. The extraction of spectra was carried out using the xselect task, as well as the associated response matrix files (RMFs) and the ancillary response files (ARFs) using the standard analysis threads$^1$. The spectra were grouped to contain 20 counts per bin using the ftool grppha. Finally, we checked that the data were not affected by pile-up using the sas task epatplot.

### 2 OBSERVATIONS AND ANALYSIS

#### 2.1 RXTE data

We analysed the RXTE observation of XTE J1719–291 taken on 2008 March 24. We extracted a spectrum from the PCA (including PCU2 only), using Standard 2 data of all layers. The background was estimated using pbackest (v. 3.6) and the faint source model. A response matrix was created using pmap (v. 10.1), taking into account the ~0.02 offset between the RXTE pointing and XTE J1719–291. We grouped the resulting spectrum to have a minimum of 50 counts per energy bin and applied a systematic error of 1 per cent.

#### 2.2 XMM–Newton data

XTE J1719–291 was observed with XMM–Newton on 2008 March 30, with an exposure time of 44 ks. The data were taken using the EPIC detectors, the two MOS and the pn CCD cameras, operated in full window mode with the medium and thick optical blocking filter, respectively. The data were processed with the standard XMM–Newton Science Analysis System (SAS v.9.0) to obtain calibrated event lists and scientific products. The observation was affected by a strong background flare. We exclude the data where the count rate exceeded 1 and 0.5 counts s$^{-1}$ for the pn and MOS data, respectively, which results in a total live time of 17 ks. The extraction of spectra was carried out using the xmmselect task, as well as the associated response matrix files (RMFs) and the ancillary response files (ARFs) using the standard analysis threads$^1$. The spectra were grouped to contain 20 counts per bin using the ftool grppha. Finally, we checked that the data were not affected by pile-up using the sas task epatplot.

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$^1$ See http://xmm.esac.esa.int/sas/current/documentation/threads/
2.3 Swift data

Six observations were carried out with the XRT. All data were collected in photon counting mode. The data were processed running the xrtpipeline task in which standard event grades of 0–12 were selected. For every observation, spectra, light curves and images were obtained with the xselect (v.2.3) package. Source spectra were extracted from a circular region with a radius of 17 pixels. For the background, three circular regions of similar size as the source region were used over nearby source-free regions. The spectra were grouped to have a minimum of five counts per energy bin with xselect.

The spectra were corrected for the fractional exposure loss due to bad columns on the CCD. For this, we created exposure maps with the xrtexpomap task, which is used as an input to generate the ARF with the xrtmkarf task. For the RMF, the latest version was used from heasarc calibration data base (v.11).

Observations 5 and 6 (see Table 1) have the highest count rates (0.5–0.7 counts s\(^{-1}\)) and might be affected by pile-up. To test this, we have used the software ximage\(^2\). We compared the point spread function of the data with that expected for the XRT, and we found that there was no pile-up.

In the last XRT observation (observation 9) the source was not detected. The upper limit on the flux was calculated with webpimms heasarc tool.\(^3\) An absorbed power-law model with a photon index of 2.74 and a hydrogen column density \(N_H\) of \(0.53 \times 10^{22}\) cm\(^{-2}\) (see Section 3) was assumed, and the count rate was calculated using the prescription for small numbers of counts given by Gehrels (1986).

2.4 Chandra data

The Chandra data analysis was performed using the High Resolution Camera (HRC-I) on 2008 April 27 for an exposure time of 2.1 ks (see also Greiner et al. 2008). We obtained these data from the Chandra data archive. The intrinsic energy resolution of the HRC-I is poor, so no spectral fitting can be carried out.

Data reduction was performed using the Chandra Interactive Analysis of Observations software (CIAO v.4.1). We calculated the net source count with the dmextract task over a circular region with a radius of 12 pixels, and the background was taken with an annulus around the source (of the inner radius of 56 pix and the outer radius of 98 pix). The flux was calculated with webpimms hearsac tool assuming a power-law model with a photon index of 2.74 and a hydrogen column density \(N_H\) of \(0.53 \times 10^{22}\) cm\(^{-2}\) (see Section 3).

3 RESULTS

To fit the spectra of the observations we used xspec (v.12.6.0). The spectra corresponding to the XMM–Newton observation (of three EPIC cameras, the pn and the two MOS) are shown in Fig. 1 and were fitted simultaneously with all parameters tied between the three detectors in order to provide the best constraints on the spectral parameters. The long effective exposure time \((\sim 17\) ks\) of this observation allows us to obtain the most accurate hydrogen column density, and it has good enough statistics to distinguish between fits using different models.

First, we tried a power-law continuum model affected by absorption. The returned photon index was 2.74 \(\pm\) 0.05 and the \(N_H\) obtained was \((0.53 \pm 0.02) \times 10^{22}\) cm\(^{-2}\). However, this model led to a poor fit (\(\chi^2 = 1.2\) for 544 d.o.f.). Adding a blackbody as a soft component the fit improves notably (\(\chi^2 = 1.06\) for 541 d.o.f.; see Fig. 1). The parameters obtained with this model are \(N_H(0.33 \pm 0.03) \times 10^{22}\) cm\(^{-2}\), which are consistent with the value found by Kalberla et al. (2005) at the source position, a photon index of 1.7 \(\pm\) 0.1 and a temperature (kT) of 0.32 \(\pm\) 0.02 keV. The soft component contributes nearly 30 per cent of the 0.5–10 keV source flux. An f-test indicates a probability of \(2.6 \times 10^{-16}\) of achieving this level of improvement by chance.

The result is almost identical if we use a multicolour disc blackbody as the soft component. The \(N_H\) was 0.37 \(\pm\) 0.03 \(\times\) \(10^{22}\) cm\(^{-2}\), the photon index was 1.6 \(\pm\) 0.1 and the temperature at the inner disc radius \((T_{\text{in}})\) was 0.45 \(\pm\) 0.03 keV.

The soft component cannot be constrained with Swift data since their statistics are poorer, and neither it can be constrained with the RXTE spectrum because it is not sensitive to energies below 2 keV. In the first attempt to study the evolution of the outburst, we calculate the X-ray colour using the Swift/XRT data only to avoid calibration uncertainties between the different instruments. The colour is defined as the ratio of counts between a hard band (2–10 keV) and a soft band (0.5–2 keV), and its values are shown in Figs 2(c) and 3(b). We see that the spectrum becomes harder during the outburst, and it turns soft again when the outburst decays. This plot of the hardness ratio (HR) shows the spectral behaviour independently of the assumed spectral model.

To exclude the possibility that the observed spectral softening is due to pile-up (see also Section 2.3), we repeat the HR calculations using annular regions to exclude the photons coming from the centre. We use annuli with an outer radius equal to the size of the circular region that was used previously (17 pixels; see Section 2.3), and three different sizes for the inner radius (7, 4 and 2 pixels). Our results using these different annuli are consistent with what is shown in Figs 2(c) and 3(b), indicating that the softening is not related to pile-up.

In order to investigate the nature of this softening, we have carried out different spectral fits. First, we tested if the thermal component of the two-component model varies. Since the poor statistics of the Swift data do not permit fitting with a two-component model, we made some assumptions. We fixed the \(N_H\) and the photon index parameters with the values obtained in the XMM–Newton fit. We took a power law to represent the accretion flow and the blackbody to represent the boundary layer. We fixed the power law/blackbody ratio

\[f = \frac{N_{\text{bb}}}{N_{\text{pl}}}\]

\[N_{\text{bb}} = 0.1\]

\[T_{\text{bb}} = 0.32\]

\[f = 0.3\]

\[N_{\text{pl}} = 0.53\]

\[\Gamma_{\text{pl}} = 2.74\]

\[N_{\text{bb}} = 0.37\]

\[T_{\text{bb}} = 1.6\]

\[f = 0.37\]

\[N_{\text{pl}} = 0.53\]

\[\Gamma_{\text{pl}} = 2.74\]

\[N_{\text{bb}} = 0.37\]

\[T_{\text{bb}} = 1.6\]

\[f = 0.37\]

\[N_{\text{pl}} = 0.53\]

\[\Gamma_{\text{pl}} = 2.74\]

\[N_{\text{bb}} = 0.37\]

\[T_{\text{bb}} = 1.6\]

\[f = 0.37\]

\[N_{\text{pl}} = 0.53\]

\[\Gamma_{\text{pl}} = 2.74\]

\[N_{\text{bb}} = 0.37\]

\[T_{\text{bb}} = 1.6\]

\[f = 0.37\]

\[N_{\text{pl}} = 0.53\]

\[\Gamma_{\text{pl}} = 2.74\]

\[N_{\text{bb}} = 0.37\]

\[T_{\text{bb}} = 1.6\]

\[f = 0.37\]

\[N_{\text{pl}} = 0.53\]

\[\Gamma_{\text{pl}} = 2.74\]

\[N_{\text{bb}} = 0.37\]

\[T_{\text{bb}} = 1.6\]

\[f = 0.37\]

\[N_{\text{pl}} = 0.53\]

\[\Gamma_{\text{pl}} = 2.74\]

\[N_{\text{bb}} = 0.37\]

\[T_{\text{bb}} = 1.6\]

\[f = 0.37\]

\[N_{\text{pl}} = 0.53\]

\[\Gamma_{\text{pl}} = 2.74\]

\[N_{\text{bb}} = 0.37\]

\[T_{\text{bb}} = 1.6\]

\[f = 0.37\]
assuming that the relative efficiencies for the disc and the boundary layer will not vary, and we let the temperature vary freely. This was only possible for the two observations with the highest count rates, observations 5 and 6 (see Table 1). The resulting temperatures are 0.46 ± 0.06 and 0.56 ± 0.09 keV, respectively. While the variation in temperature is not statistically significant, it is interesting to note that the data are consistent with the idea that only the blackbody temperature is varying.

To test the evolution along the outburst, we use a single power law with absorption, since this is the only model that can fit all observations. The two-component model is more unstable so the error estimates are much larger. The \( N_{\text{H}} \) was fixed to the value obtained from the XMM–Newton data (\( N_{\text{H}} = 0.53 \times 10^{22} \text{ cm}^{-2} \)), while the photon index and normalization components were left as free parameters. For the Chandra and the sixth Swift observation (observation 9 in Table 1), we used webpimms to convert the obtained count rate into flux using the spectral parameters obtained in the XMM–Newton fitting.

For all cases, we calculated the absorbed and unabsorbed fluxes for both the 0.5–10 and the 2–10 keV energy ranges as well as the corresponding X-ray luminosities assuming a distance of 8 kpc, given the proximity of the source to the Galactic Centre. These results are reported in Table 2.

The light curve (2–10 keV) is displayed in Fig. 2(a). In the plot we have included the four previous points from RXTE/PCA bulge scans reported by Markwardt & Swank (2008). There are two peaks in the curve and the luminosity varies by ∼2 orders of magnitude. The peak luminosity value is \( 7 \times 10^{35} \text{ erg s}^{-1} \) on 2008 May 24. This low luminosity justifies the classification as a VFXT. The upper limit on the quiescent 2–10 keV luminosity inferred from the non-detection by the Swift/XRT on 2008 May 14 (observation 9) is \( 2 \times 10^{32} \text{ erg s}^{-1} \). The outburst thus lasted at least 46 d.

In Fig. 2(b), the evolution of \( \Gamma \) in time is plotted. We see that \( \Gamma \) varies along the outburst, with values between 2 and 2.8. Comparing this figure with Fig. 2(a) it can be seen that \( \Gamma \) increases with decreasing luminosity. In order to see this softening more clearly, we show a plot of \( \Gamma \) versus \( L_{\text{X}} \) in Fig. 3(a).

### 3.1 Time-averaged accretion rate

From the mean unabsorbed outburst flux we can estimate the average mass-accretion rate during the outburst following the relation \( \langle M_{\text{obs}} \rangle = RL_{\text{acc}}/GM \), where \( G \) is the gravitational constant. \( L_{\text{acc}} \) is the 0.1–100 keV accretion luminosity which we estimate from the mean 2–10 keV unabsorbed outburst luminosity applying a bolometric correction factor of 3 (in’t Zand, Jonker & Markwardt 2007). \( R \) and \( M \) are the radius and mass of the compact object, respectively. We obtain \( \langle M_{\text{obs}} \rangle = 5.57 \times 10^{-11} \text{ M}_\odot \text{ yr}^{-1} \) for a canonical NS (i.e. \( M = 1.4 \text{ M}_\odot \), \( R = 10 \text{ km} \)) and \( \langle M_{\text{obs}} \rangle = 2.68 \times 10^{-11} \text{ M}_\odot \text{ yr}^{-1} \) for a BH (assuming \( M = 10 \text{ M}_\odot \), \( R = 34 \text{ km} \)). Once \( \langle M_{\text{obs}} \rangle \) is obtained, we determine the long-term averaged value using the relation \( \langle M_{\text{long}} \rangle = \langle M_{\text{obs}} \rangle t_{\text{ob}}/t_{\text{rec}} \), where \( t_{\text{ob}} \) is the outburst duration and \( t_{\text{rec}} \) is the system’s recurrence time, i.e. the sum of the outburst and quiescence time-scales. The factor \( t_{\text{ob}}/t_{\text{rec}} \) is the duty cycle of the system.

For XTE J1719−291, \( t_{\text{ob}} \) is at least 46 d (see Fig. 2). However, we do not know the quiescence time-scale because no other outbursts have been observed so far. We will assume a quiescence time (\( t_{\text{q}} \)) of at least nine years, which is the time since RXTE/PCA has monitored this region during Galactic bulge scans (1999 February) till the discovery of XTE J1719−291 in 2008 March. Taken this \( t_{\text{ob}} \), the duty cycle is <1.3 per cent. This results in an estimated \( \langle M_{\text{long}} \rangle \lesssim 7.7 \times 10^{-13} \text{ M}_\odot \text{ yr}^{-1} \) for an NS compact object and \( \langle M_{\text{long}} \rangle \lesssim 3.7 \times 10^{-13} \text{ M}_\odot \text{ yr}^{-1} \) for a BH. The factor \( t_{\text{ob}}/t_{\text{rec}} \) is the duty cycle of the system.

### Figure 2

(a) The light curve of XTE J1719−291 where the energy band is 2–10 keV. The first four white squares indicate RXTE values that are taken from Markwardt & Swank (2008). (b) Photon index evolution. (c) Hardness ratio evolution (ratio of counts in the hard, 2–10 keV, and soft, 0.5–2 keV, energy bands) using only the Swift data.

### Figure 3

(a) Photon index (a) and HR using only Swift data (b) (ratio of counts in the hard, 2–10 keV, and soft, 0.5–2 keV, energy bands) versus luminosity in the 2–10 keV energy band.
\( \times 10^{-13} \) M\(_{\odot}\) yr\(^{-1}\) for a BH. We note, however, that outbursts could have been missed during the periods that the source could not be observed due to solar constraints.

We also have to consider the fact that BH systems might be radiatively inefficient at low-accretion flows. Part of the generated accretion energy could be advected into the BH or converted into jet power (e.g. Blandford & Begelman 1999; Fender, Gallo & Jonker 2003; Narayan & McClintock 2008); therefore, the estimation of \( \langle M_{\text{long}} \rangle \) from the X-ray luminosity could be underestimated.

### 4 DISCUSSION

We have presented RXTE, Chandra, XMM–Newton and Swift data analysis of the 2008 outburst of the newly discovered X-ray transient XTE J1719–291. The source was discovered on 2008 March 21 during RXTE/PCA bulge scans and the outburst duration was at least 46 d (see Fig. 2). The outburst light curve shows two peaks; the unabsorbed flux varies between (1.3–9.2) \( \times 10^{-15} \) erg cm\(^{-2}\) s\(^{-1}\) (2–10 keV). Adopting a distance of 8 kpc, the inferred outburst peak luminosity is \( \sim 7 \times 10^{39} \) erg s\(^{-1}\). This luminosity lies within the very faint X-ray regime, where \( L_X \) < \( 10^{39} \) erg s\(^{-1}\). The nature of XTE J1719–291 is unknown. An accreting white dwarf is very unlikely because these systems generally exhibit outburst peak luminosities below \( 10^{39} \) erg s\(^{-1}\). Some classical novae have reached values of a few times \( 10^{34}–10^{35} \) erg s\(^{-1}\) for weeks to months, but none of them reached a value as high as we find for XTE J1719–291 (Mukai et al. 2008). Therefore, the most likely origin of this X-ray luminosity value is an NS or a BH accreting system.

#### 4.1 X-ray spectral behaviour

The high signal-to-noise ratio of the XMM–Newton spectra permits us to try different models to fit them. We found that a two-component model, blackbody as a soft component and a power law for the hard one, could fit the spectra more accurately than a single-component model. The best fit returned a temperature \( (kT) \) of 0.33 keV, an \( N_H \) of \( 0.33 \times 10^{22} \) cm\(^{-2}\) and a photon index of 1.74. The blackbody component contributes 30 per cent of the total flux (0.5–10 keV). This soft component could be thermal emission from the surface of an NS or the boundary layer. One possible cause is accretion on to the NS at very low rates (Zampieri et al. 1995), but also it can be incandescent thermal emission from the NS surface resulting from deep crustal heating (Brown, Bildsten & Rutledge 1998), which could be visible when the accretion disc becomes smaller. It was also possible to fit the spectra with a multicolour disc blackbody as the soft component (see Section 3). Therefore, the possibility that the emission comes from the accretion disc cannot be discarded. In fact, if the compact object is a BH, the soft emission has to come from the disc.

We could detect the soft component robustly only in the XMM–Newton data; the Swift data lack a sufficient signal-to-noise ratio, while RXTE’s lower energy threshold of 2 keV is too high to allow the detection of such a soft component. Therefore, in order to study the outburst spectral evolution, we fit all the data with the same model; this is a power-law continuum model affected by an equivalent hydrogen column. The photon index evolution shows that a spectral softening, in other words, luminosity and photon index are anti-correlated. As we saw in Section 3, we cannot rule out that the difference in the spectrum is produced by the blackbody soft component, i.e. the blackbody becomes stronger at lower \( L_X \). In any case, the X-ray colour diagram (Fig. 3b) confirms the softening independently of the model used.

This behaviour differs from the bright transient systems, whose spectra evolve towards the low-hard state at the end of the outburst (see van der Klis 2006; Belloni 2010). However, such softening towards even lower luminosities has been observed before in some BH transients returning to quiescence from the hard state. The photon index of XTE J1650–500 softens from 1.66 to 1.93 in the hard state at X-ray luminosities down to \( L_X = 1.5 \times 10^{34} \) erg s\(^{-1}\) (Tomsick, Kalenica & Kaaret 2004). XTE J1550–564 and XTE J1650–500 begin gradual softenings at low luminosities \( L_X \) \( \leq 10^{33} \) erg s\(^{-1}\) (Kalemci 2002). Also Corbel, Koerding & Kaaret (2008) found that the photon index of V404 Cyg is softer in quiescence than in the hard state. This behaviour is consistent with the advection-dominated accretion flow model (Esin, McClintock & Narayan 1997), which predicts a gradual softening of the power-law photon index as the luminosity drops (see e.g. discussion in Tomsick et al. 2004). However, this is not always seen for all BHs in the last part of their outbursts. Jonker et al. (2010) did not find any evidence for this softening in the decay during the 2008 outburst of H 1743–322. It is worth pointing out that the BH systems are fully described by a simple power-law model at these low luminosities, whereas we also detect a disc component in our XMM–Newton spectrum. Therefore, the softening in our

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**Table 2.** Spectral results for XTE J1719–291.

| Observation | \( \Gamma \) | \( F_{X, \text{abs}} \) \( \times 10^{-15} \) erg cm\(^{-2}\) s\(^{-1}\) | \( F_{X, \text{abs}} \) \( \times 10^{-15} \) erg cm\(^{-2}\) s\(^{-1}\) | \( L_X \) \( \times 10^{39} \) erg s\(^{-1}\) | \( F_{X, \text{abs}} \) \( \times 10^{-15} \) erg cm\(^{-2}\) s\(^{-1}\) | \( L_X \) \( \times 10^{39} \) erg s\(^{-1}\) |
|------------|-------------|----------------|----------------|----------------|----------------|----------------|
| 1          | 2.02 ± 0.08 | 112 ± 11       | 173 ± 11       | 133 ± 8        | 86.8 ± 10      | 92 ± 11        | 70 ± 8        |
| 2          | 2.74 ± 0.05 | 2.71 ± 0.13    | 6.21 ± 0.1     | 4.75 ± 0.07    | 1.63 ± 0.12    | 1.72 ± 0.12    | 1.33 ± 0.09  |
| 3          | 2.83 ± 0.25 | 1.92 ± 0.37    | 4.7 ± 0.3      | 3.4 ± 0.2      | 1.1 ± 0.4      | 1.19 ± 0.44    | 0.91 ± 0.32  |
| 4          | 2.6 ± 0.4   | 1.09 ± 0.58    | 3.37 ± 0.6     | 3.04 ± 0.31    | 1.19 ± 0.55    | 1.28 ± 0.34    | 0.98 ± 0.44  |
| 5          | 2.32 ± 0.11 | 20.5 ± 2.7     | 36.5 ± 2.5     | 27.9 ± 1.6     | 14.3 ± 2.5     | 15.3 ± 2.6     | 11.7 ± 2.0   |
| 6          | 2.15 ± 0.09 | 34.9 ± 4.0     | 57.2 ± 3.9     | 43.8 ± 2.9     | 25.9 ± 3.8     | 27.4 ± 3.9     | 20 ± 3       |
| 7          | 2.74 (fix)  | 2.57 ± 0.15    | 5.75 ± 0.34    | 4.4 ± 0.3      | 1.5 ± 0.1      | 1.61 ± 0.09    | 1.23 ± 0.07  |
| 8          | 2.7 ± 0.4   | 2.23 ± 0.66    | 4.95 ± 0.89    | 3.79 ± 0.31    | 1.36 ± 0.57    | 1.46 ± 0.80    | 1.09 ± 0.46  |
| 9          | 2.74 (fix)  | <0.05          | <0.11          | <0.08          | <0.03          | <0.03          | <0.02        |

*Note. \( N_H \) has been fixed to 0.53 \( \times 10^{22} \) cm\(^{-2}\). The value obtained from the XMM–Newton power-law fitting (see Section 3).

\( a \) Flux in units of \( 10^{-15} \) erg cm\(^{-2}\) s\(^{-1}\).

\( b \) X-ray luminosity in units of \( 10^{39} \) erg s\(^{-1}\) calculated from the unabsorbed flux by adopting a distance of 8 kpc.
source also might be due to variations in the properties of the soft component.

On the other hand, we studied a thermal component evolution (see Section 3). We found hints that the temperature increases when the spectrum is brighter and harder. This could indicate that the softening is due to the variability of the temperature of the NS surface. According to Medvedev & Narayan (2001) solutions, a hot optically thin region should be present in low L/L_{edd} NS systems, with a cooler boundary layer in the NS surface where the rotational energy is released.

4.2 Optical counterpart and orbital period
An optical/near-infrared counterpart of XTE J1719−291 was first observed by Greiner et al. (2008) during an observation made on 2008 April 11. The counterpart was observed in several optical bands (r′, r′, g′, z′) with a magnitude between 22.3 and 23.0. The closest X-ray observation in time was made on April 9 by Swift (observation 5; Table 1), with a source at a 0.5−10 keV luminosity of \sim 3 \times 10^{38} \text{ erg s}^{-1} (see Table 2). The optical counterpart was not detected in a subsequent observation made on 2008 May 4 when the X-ray luminosity was already below the sensitivity level of the Swift/XRT. Therefore, the counterpart observed on April 11 is very likely optical emission from the accretion disc.

It was shown (Russell et al. 2006, 2007a) that BHs and NSs occupy different regions of an optical−X-ray luminosity diagram when these transients are accreting at low luminosities (L_x \lesssim 10^{39} \text{ erg s}^{-1}). At a given X-ray luminosity, an NS transient is typically \sim 20 times optically fainter than that of a BH. We can therefore use the above quasi-simultaneous optical and X-ray luminosities of XTE J1719−291 to investigate the nature of its compact object by placing these data on this diagram. We estimate the de-reddened optical flux density adopting an extinction A_v = 2.11, which has been calculated using the tabulated value reported by Schlegel, Finkbeiner & Davis (1998) and by converting the value for the visual extinction of A_v = 3.3, as reported in Greiner et al. (2008). To obtain the optical monochromatic luminosity L_{\nu_i} (\nu_i = 659−665 \text{ h}) and the X-ray luminosity L_x, we assume a distance of 8 kpc and an X-ray power law with the photon index \Gamma = 2.32 (as measured for observation 5; Table 2).

In Fig. 4, we plot the optical−X-ray luminosity diagram including data of all BHs, NSs and HMXBs collected in Russell et al. (2006, 2007a,b) and overplot our data for XTE J1719−291. Errors are propagated from those quoted with the i′-band magnitude reported by Greiner et al. (2008) and the X-ray flux in Table 2. At an assumed distance of 8 kpc, XTE J1719−291 lies amongst the other NS transients in the optical−X-ray luminosity diagram (Fig. 4). At this X-ray luminosity, it is optically fainter than all the BHs in the sample, and it is \sim 20 times fainter in optical than a typical BH. This provides evidence favouring an NS accretor in this VFXT, but this alone is no proof of the nature of the compact object; the source could indeed be an unusual BH transient with a remarkably low optical/X-ray ratio.

The detection of an optical counterpart and the knowledge of the X-ray luminosity of the source are also useful to place some initial constraints on the orbital period of the system. According to van Paradijs & McClintock (1994), the absolute visual magnitude of LMXBs correlates with the orbital period of the binary and the X-ray luminosity. If we assume M(\nu) \approx M(V), the continuum spectral index is approximately flat (F_\nu \propto \nu^{-0.1}), as may be expected for an LMXB disc at low luminosities slightly redder than a typical LMXB in the outburst because the disc is probably cooler for this VFXT (Hynes 2005; Maitra & Bailyn 2008) and again adopt A_v = 2.11, we obtain M(\nu) and reach the following orbital period constraints.

If the compact object is an NS of M = 1.4 M_\odot then Log(P_{orb}) = −0.3^{+0.8}_{−1.0} \text{ hr}, whereas Log(P_{orb}) = 0.0^{+1.1}_{−0.4} in the case of a BH of M = 10 M_\odot. The orbital period is therefore in the range of 0.4 < P_{orb} < 12 h for a 10 M_\odot BH, and of 0.1 < P_{orb} < 3 h in the case of an NS accretor (1σ confidence intervals). If the system indeed hosts an NS, the binary is most likely to be compact or ultracompact since P_{orb} < 3 h, whereas this is not necessarily true for a BH system, where P_{orb} < 12 h.

Russell et al. (2006, 2007a) showed that the global empirical relations observed for a large sample of BHs and NSs can be approximated by the van Paradijs & McClintock (1994) model; however, the BHs are on average 10 times more luminous in optical than NSs. The scatter in optical monochromatic luminosity, defined as the mean of the differences between the data and the model, is ±0.29 dex for BHs and ±0.36 dex for NSs (both a factor of \sim 2). This scatter may be due to uncertainties in the distance, inclination, interstellar absorption and masses of each system, and possibly real, intrinsic effects. These effects and their scatter can be used to further constrain the likely value of the orbital period of XTE J1719−291 if it harbours either an NS or a BH. If we again assume an NS of mass M_1 = 1.4 M_\odot and a companion star of mass M_2 = 0.6 M_\odot (typical values for the sample in Russell et al. 2007a), XTE J1719−291 would be consistent with the empirical relation for NSs if its orbital period is P_{orb} = 5.0^{+1.1}_{−1.5} h. Alternatively, if the compact object is a BH, XTE J1719−291 would only be consistent with the relation for BHs if its orbital period is P_{orb} = 0.08^{+0.13}_{−0.08} h. This assumes a combined mass of the BH and companion star of M_1 + M_2 = 10 M_\odot (typical for the sample in Russell et al. 2006). The significant differences between the orbital periods derived using
the van Paradijs & McClintock (1994) and Russell et al. (2006) relations result from the empirical systematic offset between BH and NS sources found by the latter authors. The original van Paradijs & McClintock (1994) relation was normalized to a collection of data containing two data points from BHBs, and this systematic offset between BH and NS accretors was only identified in a larger collection of sources using many data points from each source (data from 15 BH candidates and 19 NSs were used in Russell et al. 2006, 2007a).

These results favour an NS accretor in XTE J1719–291, with a likely orbital period of $1.5 \lesssim P_{\text{orb}} \lesssim 17$ h. It is also worth noting $\lesssim M_{\text{417}}, -\text{yr}$

4.3 Long-term average accretion rate

We have calculated the long-term time-averaged accretion rate for both an NS and a BH accretor (see Section 3.1). We find values of $10^{-11} - 10^{-12} M_\odot $ yr$^{-1}$. These low accretion rates are difficult to explain with the current LMXB evolution models and it might be necessary to invoke exotic scenarios, such as NSs accreting from brown dwarfs or planetary companions (see King & Wijnands 2006), although detailed binary evolution calculations still need to be performed to support these conclusions. Other possibilities for these subluminous transients are the dissipation via radiatively inefficient flows of the accretion power for BHs (e.g. Fender et al. 2003; Narayan & McClintock 2008) or the ‘propeller mechanism’ for NSs, where only a fraction of the mass transferred from the donor is accreted on to the NS (e.g. Illarionov & Sunyaev 1975; Alpar 2001; Romanova et al. 2005).

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