Further X-ray observations of EXO 0748–676 in quiescence: evidence for a cooling neutron star crust

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ABSTRACT

In late 2008, the quasi-persistent neutron star X-ray transient and eclipsing binary EXO 0748–676 started a transition from outburst to quiescence, after it actively accreted for more than 24 yr. In a previous work, we discussed Chandra and Swift observations obtained during the first 5 months of this transition. Here, we report on further X-ray observations of EXO 0748–676, extending the quiescent monitoring to 1.6 yr. Chandra and XMM–Newton data reveal quiescent X-ray spectra composed of a soft, thermal component that is well fitted by a neutron star atmosphere model. An additional hard power-law tail is detected that changes non-monotonically over time, contributing between 4 and 20 per cent to the total unabsorbed 0.5–10 keV flux. The combined set of Chandra, XMM–Newton and Swift data reveals that the thermal bolometric luminosity fades from \( \sim 1 \times 10^{34} \) to \( 6 \times 10^{33} \) (D/7.4 kpc)\(^2\) erg s\(^{-1}\), whereas the inferred neutron star effective temperature decreases from \( \sim 124 \) to 109 eV. We interpret the observed decay as cooling of the neutron star crust and show that the fractional quiescent temperature change of EXO 0748–676 is markedly smaller than observed for three other neutron star X-ray binaries that underwent prolonged accretion outbursts.

Key words: accretion, accretion discs – binaries: eclipsing – stars: individual: EXO 0748–676 – stars: neutron – X-rays: binaries.

1 INTRODUCTION

EXO 0748–676 is an intensively studied low-mass X-ray binary that was discovered with the European X-ray Observatory SATellite (EXOSAT) in 1985 February (Parmar et al. 1985). However, in retrospect the source had already appeared active in EXOSAT slew survey observations several times beginning 1984 July (Reynolds et al. 1999), whereas the earliest detection dates back to 1980 May, when EXO 0748–676 was serendipitously observed with the EINSTEIN satellite (Parmar et al. 1986). The system exhibits irregular X-ray dips and displays eclipses that last for \( \sim 8.3 \) min and recur every 3.82 h, which allow the unambiguous determination of the orbital period of the binary (Parmar et al. 1986; Wolff et al. 2009).

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The detection of type-I X-ray bursts (e.g. Gottwald et al. 1986) conclusively identifies the compact primary as a neutron star. A few X-ray bursts have been observed that exhibited photospheric radius expansion (PRE), which indicates that the Eddington luminosity is reached near the burst peak and allows for a distance estimate towards the source (Wolff et al. 2005; Galloway et al. 2008a). For a helium-dominated photosphere, a distance of \( D = 7.4 \pm 0.9 \) kpc can be derived, while assuming solar composition results in a distance estimate of \( D = 5.9 \pm 0.9 \) kpc (Galloway et al. 2008a). The rise time and duration of the PRE bursts observed from EXO 0748–676 suggest pure helium ignition, rendering 7.4 kpc as the best distance estimate (Galloway et al. 2008a), although this value is subject to several uncertainties (Wolff et al. 2005; Galloway, Özel & Psaltis 2008b).

At the time of its discovery, EXO 0748–676 was detected at 2–10 keV luminosities of \( \sim (1 - 7) \times 10^{36} \) (D/7.4 kpc)\(^2\) erg s\(^{-1}\) (Parmar et al. 1986). However, during the EINSTEIN observation of 1980, several years prior to the EXOSAT detections, it displayed a 0.5–10 keV luminosity of \( \sim 5 \times 10^{33} \) (D/7.4 kpc)\(^2\) erg s\(^{-1}\) (Parmar et al. 1986).
RXTE observations, which were performed when the source dropped below the detection limit of RXTE (both of the ASM and the PCA). All three systems were subsequently monitored with Chandra and XMM–Newton, which revealed that thermal flux and neutron star temperature were gradually decreasing over the course of years (see also Section 4). This can be interpreted as cooling of the neutron star crust that has been heated during the prolonged accretion outburst. Successful modelling of the observed quiescent X-ray light curves with neutron star thermal evolution models supports this hypothesis and provides important constraints on the crust properties, such as the thermal conductivity (Sh×ler et al. 2007; Brown & Cumming 2009).}

Although the soft spectral component has been ascribed to low-level accretion (Zampieri et al. 1995), it is most often interpreted as thermal surface radiation from the cooling neutron star (Brown, Bildsten & Rutledge 1998). According to this model, the accretion of matter compresses the neutron star crust, which induces a series of electron captures, neutron emissions and pycnonuclear fusion reactions (e.g. Haensel & Zdunik 1990, 2003, 2008; Gupta et al. 2007). The heat energy released in these processes is spread over the neutron star via thermal conduction.

The neutron star cools primarily via neutrino emissions from the stellar core, as well as photon radiation from the surface. The former depends on the equation of state of cold nuclear matter and the central density of the neutron star (e.g. Yakovlev & Pethick 2004; Page, Geppert & Weber 2006). The neutron star core reaches a thermal steady state in $\sim10^3$ yr, yielding an incandescent emission from the neutron star surface set by the time-averaged accretion rate of the system, as well as the rate of neutrino emissions from the stellar core (e.g. Brown et al. 1998; Colpi et al. 2001). When combined with estimates of the outburst history, observations of quiescent neutron stars can constrain the rate of neutrino emissions, thereby providing insight into the interior properties of the neutron star (e.g. Heinke et al. 2009).

Once the steady state is reached, the neutron star core temperature will not change appreciably during a single outburst, but the temperature of the crust can be dramatically altered. In regular transients that have a typical outburst duration of weeks to months, the crustal heating processes will only cause a slight increase in the crust temperature (Brown et al. 1998). However, in quasi-persistent X-ray binaries the prolonged accretion episodes can cause a significant temperature gradient between the neutron star crust and core. Once the accretion ceases, the crust is expected to thermally relax on a time-scale of years, until equilibrium with the core is re-established (Rutledge et al. 2002). During the initial stages of the quiescent phase the thermal emission will therefore be dominated by the cooling crust, whereas eventually a quiescent base level is reached that is set by the thermal state of the core (Wijnands et al. 2001; Rutledge et al. 2002). This provides the special opportunity to separately probe the properties of the neutron star crust (Haensel & Zdunik 2008; Brown & Cumming 2009).

In 2001, the neutron star X-ray binaries KS 1731–260 and MXB 1659–29 both made the transition to quiescence, following accretion episodes of 12.5 and 2.5 yr, respectively (Wijnands et al. 2001, 2002, 2003, 2004; Cackett et al. 2006, 2008). More recently, in 2007, the $\sim$1-yr long outburst of XTE J1701–462 came to a halt (Altamirano et al. 2007; Homan et al. 2007; Fridriksson et al. 2010). All three systems were subsequently monitored with Chandra and XMM–Newton, which revealed that thermal flux and neutron star temperature were gradually decreasing over the course of years (see also Section 4). This can be interpreted as cooling of the neutron star crust that has been heated during the prolonged accretion outburst. Successful modelling of the observed quiescent X-ray light curves with neutron star thermal evolution models supports this hypothesis and provides important constraints on the crust properties, such as the thermal conductivity (Sh×ler et al. 2007; Brown & Cumming 2009).

Along these lines we have pursued an observational campaign of EXO 0748–676 to study the time evolution of the quiescent X-ray emission following its long accretion outburst. In Degenaar et al. (2009), we discussed Chandra and Swift observations obtained between 2008 September 28 and 2009 January 30. We found...
a relatively hot and luminous quiescent system with a temperature of \(kT_{\text{eff}} \sim 0.11–0.13\) keV and a thermal 0.01–100 keV luminosity of \(\sim (8–16) \times 10^{33}\) (D/7.4 kpc)\(^2\) erg s\(^{-1}\). No clear decrease in effective temperature and thermal bolometric flux was found over the 5-month time-span. In this paper we report on continued Swift and Chandra observations of EXO 0748–676 during its quiescent state. In addition, we include an archival XMM–Newton observation performed \(\sim\)2 months after the cessation of the outburst. Previous Chandra and Swift observations discussed by Degenaar et al. (2009) were re-analysed in this work in order to obtain a homogeneous quiescent light curve.

2 OBSERVATIONS AND DATA ANALYSIS

Table 1 gives an overview of all new observations of EXO 0748–676 discussed in this paper. A list of earlier Chandra and Swift observations obtained during the quiescent phase can be found in Degenaar et al. (2009).

### Table 1. Observation log.

| Satellite | Obs. ID | Date       | Exp. time (ks) |
|-----------|---------|------------|----------------|
| XMM       | 0560180701* | 2008-11-06 | 29.0 (MOS) 22.9 (PN) |
| Swift     | 31272016  | 2009-02-13 | 3.5            |
| Swift     | 31272017  | 2009-02-20 | 4.1            |
| Swift     | 31272018* | 2009-02-23 | 5.1            |
| Chandra   | 9071*    | 2009-02-23/24 | 15.8          |
| Swift     | 10871*   | 2009-02-25 | 9.6            |
| Swift     | 31272019* | 2009-03-01 | 3.2            |
| Swift     | 31272020  | 2009-03-10 | 5.1            |
| Swift     | 31272021  | 2009-03-16 | 4.6            |
| Swift     | 31272022  | 2009-04-09 | 3.5            |
| Swift     | 31272023  | 2009-04-16 | 2.8            |
| Swift     | 31272024  | 2009-04-23 | 4.8            |
| Swift     | 31272025  | 2009-05-07 | 4.5            |
| Swift     | 31272026  | 2009-05-14 | 3.6            |
| Swift     | 31272027  | 2009-05-28 | 3.4            |
| Swift     | 31272028  | 2009-06-05 | 4.1            |
| Chandra   | 9072*    | 2009-06-10 | 27.2           |
| Swift     | 31272029* | 2009-06-11 | 4.3            |
| Swift     | 31272030  | 2009-06-18 | 3.9            |
| Swift     | 31272031* | 2009-06-26 | 5.5            |
| Swift     | 31272032* | 2009-07-03 | 4.8            |
| Swift     | 31272033  | 2009-07-18 | 5.5            |
| Swift     | 31272034* | 2009-07-25 | 5.8            |
| Swift     | 31272035* | 2009-07-31 | 10.3           |
| Swift     | 31272036* | 2009-08-15 | 9.4            |
| Swift     | 31272037  | 2009-08-25 | 1.1            |
| Swift     | 31272038  | 2009-08-26 | 7.4            |
| Swift     | 31272039* | 2009-09-08 | 4.7            |
| Swift     | 31272040* | 2009-09-09 | 4.3            |
| Swift     | 31272041  | 2009-10-01 | 1.9            |
| Swift     | 31272042  | 2009-10-02 | 1.8            |
| Swift     | 31272043  | 2009-10-07 | 2.0            |
| Swift     | 31272044  | 2009-10-08 | 2.4            |
| Swift     | 31272045  | 2009-10-09 | 2.3            |
| Swift     | 31272046* | 2009-11-05 | 4.2            |
| Swift     | 31272047* | 2009-12-21 | 9.4            |
| Swift     | 31272048* | 2010-10-01 | 9.6            |
| Swift     | 31272049  | 2010-02-12/13 | 11.3          |
| Swift     | 31272050* | 2010-03-12/13 | 9.5          |
| Chandra   | 11059*   | 2010-04-20 | 27.4           |

Note – The observations marked with an asterisk contain (part of) eclipses. The listed exposure times represent the duration of the observations uncorrected for eclipses.

### 2.1 XMM–Newton

EXO 0748–676 was observed with the European Photon Imaging Camera (EPIC) onboard XMM–Newton on 2008 November 6 08:30–16:42 UT (see also Bassa et al. 2009). The EPIC instrument consists of two MOS detectors (Turner et al. 2001) and one PN camera (Strüder et al. 2001), which are sensitive in the 0.1–15 keV energy range and have effective areas of 922 and 1227 cm\(^2\) (at 1 keV), respectively. Both the PN and the two MOS instruments were operated in full window mode and using the medium optical blocking filter. Data reduction and analysis was carried out with the Science Analysis Software (SAS; v. 9.0.0). We reprocessed the original data files (ODF) using the tasks EMPROC and EPPROC. To identify possible periods of high particle background, we extracted high-energy light curves (\(\geq 10\) keV for the MOS and between 10–12 keV for the PN). No strong background flares occurred during the observation. The net exposure times are 29.0 and 22.9 ks for the MOS and PN, respectively. EXO 0748–676 is detected at count rates of 0.16 \(\pm\) 0.01 counts s\(^{-1}\) (MOS) and 0.55 \(\pm\) 0.01 counts s\(^{-1}\) (PN).

Source spectra and light curves were obtained with the software task EVSELECT, using a 35 arcsec circular region and applying pattern selections 0–12 and 0–4 for the MOS and PN data, respectively. Corresponding background events were extracted from a circular region with a radius of 70 arcsec. For the MOS cameras, the background was positioned on a source-free region on the same CCD as the source. For the PN instrument, the background events were extracted from an adjacent CCD, at the same distance from the readout node to ensure similar low-energy noise. The ancillary response files (arf) and redistribution matrices (rmf) were generated for each of two MOS and the PN cameras with the tasks ARFGEN and RMFGEN.

The EPIC light curves show two full eclipses (see also Bassa et al. 2009), corresponding to eclipse cycles 54 384 and 54 385 in the numbering system of Parmar et al. (1986). To calculate the correct non-eclipse time-averaged fluxes, we reduce the exposure times for each instrument by 500 s per eclipse, which is the approximate length of the eclipses of EXO 0748–676 (Wolff et al. 2009).\(^1\) Using the tool GRPPHA, the spectra were grouped to contain a minimum of 20 photons per bin.

### 2.2 Chandra

We obtained three new Chandra observations of EXO 0748–676 using the S3 chip of the Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003). The ACIS detector is sensitive in the 0.1–10 keV passband and has an effective area of 340 cm\(^2\) at 1 keV. The first observation consists of two separate exposures obtained on 2009 February 23–24 22:07–03:15 UT (obs ID 9071) and 2009 February 25 12:32–15:59 UT (obs ID 10871), lasting for \(\sim\)15.8 and \(\sim\)9.6 ks, respectively. In both data sets, EXO 0748–676 is clearly detected at a count rate of 0.17 \(\pm\) 0.01 counts s\(^{-1}\). This is a factor of \(\sim 1.5\) lower than observed in 2008 October, when the source was detected with Chandra/ACIS-S at a rate of 0.24 \(\pm\) 0.01 counts s\(^{-1}\).

Two full eclipses are seen in the light curve of observation 9071,\(^1\) As shown by Wolff et al. (2009), the duration of the eclipses of EXO 0748–676 varied between \(\sim\)484 and 512 s over the years 1996–2008. These small uncertainties in the eclipse duration do not affect our results.

\(^1\)As shown by Wolff et al. (2009), the duration of the eclipses of EXO 0748–676 varied between \(\sim\)484 and 512 s over the years 1996–2008. These small uncertainties in the eclipse duration do not affect our results.
This is the case for obs IDs 31272037/38, 31272039/40 and 1409–1418; for all three observation sequences, Swift UT and −<−−< account for vignetting and point-spread-function correction. We fitted the spectral data in the 0.5–10 keV energy range using XSPEC (v. 12.0; Arnaud 1996). This software package facilitates fitting a spectral model simultaneously to multiple data files, which each have their own response and background files. As is common practice, we fit the XMM–Newton data with all spectral parameters tied between the different detectors (i.e. the model parameters are not allowed to vary independently between the PN and two MOS detectors). For all fits throughout this paper, we included the effect of neutral hydrogen absorption, NH, along the line of sight using the PHABS model with the default XSPEC abundances (Anders & Grevesse 1989) and cross-sections (Balucinska-Church & McCammon 1992).

We first investigate the shape of the quiescent spectrum of EXO 0748–676 by considering the XMM–Newton observation, which provides the highest statistics. A single absorbed power-law (POWERLAW in XSPEC) provides an acceptable fit to the data (χ^2 = 1.3 for 466 d.o.f.). However, the spectral index is unusually large for an X-ray binary (Γ = 4.7 ± 0.1) and suggests that the spectrum has a thermal shape. Using a simple absorbed blackbody model, BBODYRAD, results in an adequate fit (χ^2 = 1.2 for 466 d.o.f.), although the inferred emitting region has a much smaller radius than expected for a neutron star (~2–4 km for distances of 5–10 kpc). Nevertheless, it is thought that radiative transfer effects in the neutron star atmosphere cause the emergent spectrum to deviate from a blackbody (e.g. Zavlin, Pavlov & Shibanov 1996; Rutledge et al. 1999). There are several neutron star atmosphere models available within XSPEC, which yield equivalent results (see e.g. Heinke et al. 2006; Webb & Barret 2007). In the remainder of this work, we

2 This is the case for obs IDs 31272037/38, 31272039/40 and 31272043/44/45; see Table 1.
concentrate on fitting the data with a neutron star atmosphere model NSATMOS (Heinke et al. 2006).

The NSATMOS model consists of five parameters, which are the neutron star mass and radius (\(M_{NS}\) and \(R_{NS}\)), the effective temperature in the neutron star frame (i.e. non-redshifted; \(kT_{eq}\)), the source distance (\(D\)) and a normalization factor, which parametrizes the fraction of the surface that is radiating. We keep the latter fixed at 1 throughout this work, which corresponds to the entire neutron star surface emitting. The effective temperature as seen by an observer at infinity is given by \(kT_{eq} = kT_{eq}/(1+z)\), where \(1+z = (1-R_{NS}/R_{NS})^{-1/2}\) is the gravitational redshift factor, with \(R_{NS} = 2GM_{NS}/c^2\) being the Schwarzschild radius, \(G\) the gravitational constant and \(c\) the speed of light.

The XMM–Newton data is well fitted by an absorbed NSATMOS model (\(\chi^2 = 1.1\) for 466 d.o.f.), although significant residuals above the model fit are present for energies \(\gtrsim 2\)–\(3\) keV. We model this non-thermal emission by adding a power-law component, which significantly improves the fit (\(\chi^2 = 1.0\) for 464 d.o.f.; an F-test suggests a \(\sim 1 \times 10^{-14}\) probability of achieving this level of improvement by chance). Chandra observations carried out in 2008 mid-October, three weeks prior to this XMM–Newton observation, also indicated the presence of a non-thermal component in the quiescent spectrum of EXO 0748–676 (Degenaar et al. 2009). Whereas the Chandra data could not constrain the power-law index, the larger collective area of XMM–Newton provides better constraints for the fluxes under consideration.

By using a combined NSATMOS and powerlaw model to fit the XMM–Newton data, we obtain a power-law index of \(\Gamma = 1.7 \pm 0.5\), i.e. in between the values of \(\Gamma = 1\) and \(\Gamma = 2\) considered by Degenaar et al. (2009). This fit furthermore yields \(N_H = (7 \pm 2) \times 10^{20}\) cm\(^{-2}\) and \(R_{NS} = 17.8 \pm 1\) km, when fixing the neutron star mass to a canonical value of \(M_{NS} = 1.4\) M\(_\odot\) and the distance to \(D = 7.4\) kpc (the best estimate from type-I X-ray burst analysis; Galloway et al. 2008a). The resulting power-law component contributes \(\sim 10\) per cent to the total unabsorbed 0.5–\(10\) keV flux. This is lower than the \(\sim 15–20\) per cent inferred from the Chandra observations performed in 2008 mid-October (Degenaar et al. 2009). The obtained hydrogen column density is consistent with values found for EXO 0748–676 during its outburst (\(N_H \sim 7 \times 10^{20} \sim 1.2 \times 10^{21}\) cm\(^{-2}\); e.g. Sidoli, Parmar & Oosterbroek 2005).

The Chandra observations obtained in 2009 February and June are well fitted by an absorbed NSATMOS model and do not require an additional power-law component. However, the 2010 April data show evidence for such a hard tail, as significant residuals are present above the NSATMOS model fit for energies \(\gtrsim 2\)–\(3\) keV. If we include a power law with photon index \(\Gamma = 1.7\), as was found from fitting the XMM–Newton data (see above), this model component contributes \(\sim 10\), \(\sim 5\) and \(\sim 15\) per cent to the total unabsorbed 0.5–\(10\) keV flux for the data taken in 2009 February, June and 2010 April, respectively. Fig. 3 compares the Chandra spectral data obtained on 2008 October and 2010 April, showing that both spectral components decreased over the 18-month time-span that separates the two observations. We found no spectral differences between the two separate exposures performed in 2009 February and therefore we tied all spectral parameters between these two spectra in the fits.

The Swift data do not provide sufficient statistics to constrain the presence of a hard spectral component. We do include a powerlaw in the fits, but fix both the index and the normalization of this component (see Section 3.1). Since it is unclear how the power law exactly evolves over time, we adjust the power-law normalization for the Swift observations such that it always contributes 10 per cent of the total unabsorbed 0.5–\(10\) keV flux. After treating each Swift observation separately, we found that the thermal flux and neutron star temperature did not evolve significantly between consecutive observations. To improve the statistics, we therefore sum the Swift data into groups spanning \(\sim 1–4\) weeks of observations, resulting in exposure times of \(\sim 10–20\) ks (see Table 2). The summed spectra were grouped to contain a minimum of 20 photons per bin.

3 RESULTS

3.1 Spectral fits

As discussed in Section 2.4, the quiescent spectrum of EXO 0748–676 can be described by a combination of a neutron star atmosphere model and a non-thermal power-law tail. We fitted the Chandra and XMM–Newton data simultaneously within xspec to a combined NSATMOS and powerlaw model subject to interstellar absorption, to explore the best-fitting values for the neutron star mass and radius, source distance and hydrogen column density. We include the first set of Chandra observations obtained in 2008 October (discussed in Degenaar et al. 2009) in the analysis. As before, we use the phabs model with the default xspec abundances and cross-sections to take into account the neutral hydrogen absorption along the line of sight. The power-law index is fixed to \(\Gamma = 1.7\) (the best-fitting value obtained from XMM–Newton observations; see Section 2.4), because there are not sufficient counts at higher energies in the Chandra spectra to allow this component to vary.

The power-law normalization is left as a free parameter. If the neutron star mass and radius are fixed to canonical values of \(M_{NS} = 1.4\) M\(_\odot\) and \(R_{NS} = 10\) km, and in addition the source distance is fixed to \(D = 7.4\) kpc, the hydrogen column density pegs at its lower limit (\(N_H = 0\)). When the distance is left to vary freely, the best-fitting value is \(4.6 \pm 0.3\) kpc, which is just outside the range obtained from X-ray burst analysis (5–8.3 kpc; Galloway et al. 2008a). Therefore, we choose to keep the distance fixed at 7.4 kpc, and instead allow the neutron star radius to vary. This way, we obtain best-fitting values of \(N_H = (7 \pm 1) \times 10^{20}\) cm\(^{-2}\) and \(R = 15.6 \pm 0.8\) km. If additionally the neutron star mass is left free to vary in the fit, this parameter is not strongly constrained (\(M_{NS} \sim 1.6 \pm 0.6\) M\(_\odot\)). In the final fits we choose to fix the neutron...
star mass to $M_{\text{NS}} = 1.4 M_\odot$, because otherwise the uncertainty in this quantity will dominate the errors of the other parameters.

For the final spectral analysis, we fit all XMM–Newton, *Chandra* and *Swift* data with an absorbed *XSPEC* model and a power-law model, where $N_H = 7 \times 10^{20} \, \text{cm}^{-2}$, $M_{\text{NS}} = 1.4 M_\odot$, $R_{\text{NS}} = 15.6 \, \text{km}$, $D = 7.4 \, \text{kpc}$ and $\Gamma = 1.7$ were kept fixed. The quoted errors represent 90 per cent confidence levels. $F_X$ represents the 0.5–10 keV total model flux and $F_{\text{bol}}$ gives the 0.01–100 keV *XSPEC* flux; both are unabsorbed and in units of $10^{-12} \, \text{erg cm}^{-2} \, \text{s}^{-1}$. $L_{\text{bol}}$ gives the 0.01–100 keV luminosity of the *XSPEC* model component in units of $10^{33} \, \text{erg s}^{-1}$ and assuming a source distance of $D = 7.4 \, \text{kpc}$. $\Delta t$ represents the time interval of the observations in days and the fractional power-law contribution is given in a percentage of the total unabsorbed 0.5–10 keV flux.

### 3.2 Light-curve fits

Fig. 4 clearly reveals a decaying trend in thermal flux and temperature. To investigate the decay shape, we fit the temperature curve with an exponential decay function of the form $T(t) = \alpha e^{-(t-t_0)/\tau}$, where $\alpha$ is a normalization constant, $t_0$ is the start time of the cooling curve and $\tau$ the e-folding time. Given the apparent offset between the different instruments (see Section 3.3), we perform different fits to the *Chandra* and *Swift* data. We fix $t_0$ to 2009 September 5 (MJD 54714), which is in between the first non-detection by *RXTE/PCA* and the first *Swift/XRT* observation of the source (Degenaar et al. 2009).

![Figure 4](https://example.com/fig4.png)

Figure 4. Evolution of the bolometric flux (top) and effective temperature (bottom) of EXO 0748–676, detected from *Chandra/ACIS-S* (black squares), *Swift/XRT* (grey triangles) and *XMM–Newton/EPIC* (black star) data. Multiple *Swift* observations were summed to improve the data statistics (see Section 2.4).

The simple exponential decay, represented by the dotted lines in Fig. 5, yields an e-folding time of $612 \pm 2004 \, \text{d}$ for the *Chandra* data, but does not provide a good fit ($\chi^2 = 6.0$ for 2 d.o.f.). For the *Swift* light curve we find $\tau = 5328.1 \pm 674.7 \, \text{d}$ ($\chi^2 = 0.5$ for 12 d.o.f.). If we include a constant offset [i.e. $y(t) = \alpha e^{-(t-t_0)/\tau} + b$; solid lines in Fig. 5], we obtain a better fit for the *Chandra* data, yielding a normalization of $\alpha = 13.4 \pm 0.2 \, \text{eV}$, an e-folding decay...
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A = 134.4 ± 1.0 eV (χ^2 = 0.13 for 2 d.o.f.). For the Swift observations we find

B = 0.05 ± 0.01 and

A = 144.7 ± 3.8 eV (χ^2 = 0.4 for 12 d.o.f.). These power-law fits are indicated by the
dashed line in Fig. 5.

A broken power law also yields an acceptable fit to the Swift data (χ^2 = 0.3 for 10 d.o.f.). We find a normalization of

A = 135.0 ± 17.8 eV, a break at 166.0 ± 99.2 d and decay indices of

−0.03 ± 0.03 and

−0.06 ± 0.02 before and after the break, respectively. This fit is indicated by the dashed–dotted curve in Fig. 5. There are not sufficient

Chandra

observations to fit a broken power-law decay. We note that the shape of the decay curve of EXO 0748–676 is not strongly affected by our choice of spectral parameters (NH, MNS, RNSS and Γ) or assumed distance (see also previous studies by e.g. Wijnands et al. 2004; Cackett et al. 2008).

3.3 Instrument cross-calibration

The quiescent light curve presented in Fig. 4 shows indications that the thermal flux and temperature inferred from the

Chandra

observations lie below the trend of the Swift data points. This possible shift (~6 per cent for the flux light curve) may be due to cross-calibration issues between the two satellites. A study of the Crab nebula indeed revealed an offset between

Chandra

and

Swift

, whereas such a discrepancy was not found between

Swift

and

XMM–Newton (Kirsch et al. 2005). This might be reflected in our results as well, since the

XMM–Newton

data point appears to line up with the trend indicated by the

Swift

data. However, our

Chandra

and

Swift

data points may also be (partly) offset due to the fact that we cannot constrain the power-law component in the

Swift

data, which we therefore fixed to contribute 10 per cent of the total 0.5–10 keV unabsorbed flux (see Section 2.4).

4 DISCUSSION

We discuss

Chandra

, Swift and

XMM–Newton observations obtained after the cessation of the very long (~24 yr) active period of EXO 0748–676. Fitting the spectral data with a neutron star atmosphere model NSATMOS, did not reveal clear indications of a changing thermal spectrum during the first 5 months of the quiescent phase (Degenaar et al. 2009). However, now that the quiescent monitoring has extended to 19 months (1.6 yr), we find a significant decrease in neutron star effective temperature from kTeff ~ 124 to 109 eV. The thermal bolometric flux was observed to decay from F_{bol}^\infty ~ 1.5 \times 10^{-12} to 0.9 \times 10^{-12} erg cm^{-2} s^{-1}.

In addition to a soft, thermal component, the

Chandra

and

XMM–Newton observations show evidence for a hard power-law tail with index Γ = 1.7. The fractional contribution of the hard spectral component to the total unabsorbed 0.5–10 keV flux initially decreased from ~20 per cent in 2008 October to ~4 per cent in 2009 June. However, observations carried out in 2010 April suggest that the power-law fraction increased again to ~15 per cent. Similar behaviour has been observed for several other quiescent neutron star systems (Jonker et al. 2004; Jonker 2008), although others show more irregular behaviour (Fridriksson et al. 2010). In Cen X-4, the power-law tail in the quiescent spectrum shows variations that appear to be linked to changes in the thermal component, possibly caused by low-level accretion (Cackett et al. 2010).

The gradual decrease in thermal flux and neutron star temperature observed for EXO 0748–676 can be interpreted as the neutron star crust cooling down in quiescence after it has been heated during its long accretion outburst. Fig. 6 compares our data of EXO 0748–676 with the crust cooling curves observed for the neutron star X-ray binaries KS 1731–260, MXB 1659–29 and XTE J1701–462. This

Figure 5. Evolution of the effective temperature of EXO 0748–676 fitted to different decay functions (see Section 3.2). The left image displays

Chandra

data and exponential decay fits both with and without a constant offset (solid and dotted line, respectively), as well as a decaying power law (dashed curve). The right image shows

Swift

observations, where the dashed line is again a power-law fit, while the solid and dotted curves are exponential decays. In addition, this plot includes a fit to a broken power law, which is represented by the dashed–dotted line.
The effective temperatures of KS 1731−260 (green diamonds; from Cackett et al. 2006), MXB 1659−29 (red bullets; from Cackett et al. 2006, 2008), XTE J1701−462 (grey crosses; from Fridriksson et al. 2010) and EXO 0748−676 (black squares, triangles and star). Exponential decay fits to the data of KS 1731−260, MXB 1659−29 and XTE J1701−462 are shown to guide the eye (green dashed, red dashed-dotted and grey dotted line, respectively). The two data points of XTE J1701−462 that lie above the decay fit are likely due to a temporary increase in the accretion rate causing reheating of the neutron star (Fridriksson et al. 2010). The plot shows that the amount of cooling following the end of the outburst is markedly smaller for EXO 0748−676 than for the other three sources. We have observed our target over the first 19 months after the cessation of the outburst and during this time the thermal bolometric flux has decreased by a factor of $\sim 1.7$. In a similar time-span, the thermal bolometric fluxes of KS 1731−260, MXB 1659−29 and XTE J1701−462 had decreased by a factor of $\sim 3.5$, 6 and 2.5, respectively (see Cackett et al. 2006; Fridriksson et al. 2010). The effective neutron star temperature of EXO 0748−676 has decreased by about 10 per cent, compared to $\sim 30$, 40 and 20 per cent for KS 1731−260, MXB 1659−29 and XTE J1701−462.

Although the observed fractional changes in neutron star temperature and thermal bolometric flux are smaller for EXO 0748−676 than for the other three sources, the decay itself may not be markedly different. The quiescent light curves of KS 1731−260, MXB 1659−29 and XTE J1701−462 can be fit with an exponential decay function levelling off to a constant value, yielding e-folding times of $\sim 305 \pm 50$, $\sim 465 \pm 25$ and $\sim 120 \pm 25$ days, respectively (Cackett et al. 2008; Fridriksson et al. 2010). For the Chandra data of EXO 0748−676, we find an e-folding time of $\sim 192 \pm 10$ days (see Section 3.2). These decay times provide a measure of the thermal relaxation time of the neutron star crust, which depends on the composition and structure of the lattice, the distribution of heating sources and the thickness of the crust (e.g. Lattimer et al. 1994; Rutledge et al. 2002; Shfernirn et al. 2007; Brown & Cumming 2009).

Rutledge et al. (2002) and Shfernirn et al. (2007) calculate theoretical cooling curves for KS 1731−260, assuming different physics for the crust and core. These authors present simulations for both an amorphous crust and an ordered crystalline lattice. For the latter, the spread of nuclide charge numbers ($Z$) in the crust matter is small, which is referred to as a low level of impurities and results in a highly conductive crust. A large number of impurities gives an amorphous structure, which affects the thermal properties of the crust and results in a low conductivity. In addition, Rutledge et al. (2002) explore standard (i.e. slow) and enhanced neutrino cooling mechanisms, yielding different core temperatures. Comparing our results on EXO 0748−676 with the decay shapes resulting from those calculations suggests that the neutron star has a highly conductive crust, similar to what has been inferred for the other three sources (Wijnands et al. 2002, 2004; Cackett et al. 2006; Shfernirn et al. 2007; Brown & Cumming 2009; Fridriksson et al. 2010). The fact that the decay curve of EXO 0748−676 is rather shallow may be explained in terms of a relatively small temperature gradient and thus a lower thermal flux across the core-crust boundary (cf. the model curves for a highly conductive crust and different core temperatures presented by Rutledge et al. 2002). This can be due to a combination of a warm neutron star core and a relatively low mass-accretion rate during outburst.

The exponential decay fit to the Chandra data of EXO 0748−676 indicates that the neutron star crust might already be close to restoring equilibrium with the core. The fit results in a quiescent base level of $107.9 \pm 0.2$ eV, while we found a temperature of $108.6 \pm 1.1$ eV for the observation performed in 2010 April. Prior to its last outburst, EXO 0748−676 was observed in quiescence with the Einstein observatory, displaying a $0.5–10$ keV unabsorbed flux of $8.4^{+4.7}_{−1.7} \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ (Garcia & Callanan 1999). Our Chandra observations of 2010 April detected EXO 0748−676 at a $0.5–10$ keV unabsorbed flux of $(7.7 \pm 0.2) \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ (see Table 2). Assuming that the $\text{EINSTEIN}$ detection caught EXO 0748−676 at its quiescent base level, this supports the idea that the crust has nearly cooled down. This would imply that the neutron star core in EXO 0748−676 is relatively hot (cf. Heinke et al. 2009), suggesting that either standard cooling mechanisms are operating and that the neutron star is not very massive, or that the time-averaged mass-accretion rate of the system is very high due to a short recurrence time (see below).

The energy deposited during outburst is given by $L_{\text{acc}} \sim \langle M \rangle Q_{\text{acc}}/m_{\text{ns}}$ (e.g. Brown et al. 1998; Colpi et al. 2001). Here, $Q_{\text{acc}} \sim 2$ MeV is the nuclear energy deposited per accreted baryon (Gupta et al. 2007; Haensel & Zdunik 2008), $m_{\text{ns}}$ is the atomic mass unit and $\langle M \rangle$ is the time-averaged accretion rate of the system. The latter can be expressed as $\langle M \rangle = \langle M_{\text{obs}} \rangle \times t_{\text{obs}}/t_{\text{rec}}$, where $\langle M_{\text{obs}} \rangle$ is the average accretion rate during outburst episodes, $t_{\text{obs}}$ is the outburst duration and $t_{\text{rec}}$ is the system’s recurrence time. The factor $t_{\text{obs}}/t_{\text{rec}}$ represents the duty cycle of the system. The neutron star core is expected to be in a steady state, in which the energy radiated during quiescence balances the heat deposited during outburst. We can thus obtain an estimate of the duty cycle of EXO 0748−676 by equating the heating and cooling rates.

A neutron star cools primarily via photon radiation from the surface and neutrino emissions from the stellar core. If the light curve of EXO 0748−676 has indeed (nearly) levelled off, the bolometric luminosity emitted as photons is thus $L_{\gamma} \sim 6 \times 10^{37}$ (D/7.4 kpc)$^2$ erg s$^{-1}$ (as measured during the Chandra observation of 2010 April). The rate of neutrino emissions depends on the temperature of the neutron star core, which can be estimated from the effective surface temperature once the crust has thermally relaxed. A quiescent base level of $kT_{\text{eff}} \sim 108$ eV (as suggested by exponential decay fits to the Chandra data), implies an effective surface temperature in the neutron star frame of $kT_{\text{eff}} \sim 140$ eV ($\sim 1.6 \times 10^8$ K), for the canonical values of $M_{\text{NS}} = 1.4M_{\odot}$ and $R_{\text{NS}} = 10$ km (i.e. $1+z = 1.3$). Using the relation between

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Figure 6. The effective temperatures of KS 1731−260 (green diamonds; from Cackett et al. 2006), MXB 1659−29 (red bullets; from Cackett et al. 2006, 2008), XTE J1701−462 (grey crosses; from Fridriksson et al. 2010) and EXO 0748−676 (black squares, triangles and star). Exponential decay fits to the data of KS 1731−260, MXB 1659−29 and XTE J1701−462 are shown to guide the eye (green dashed, red dashed-dotted and grey dotted line, respectively). The two data points of XTE J1701−462 that lie above the decay fit are likely due to a temporary increase in the accretion rate causing reheating of the neutron star (Fridriksson et al. 2010).
the effective surface temperature and the interior temperature calculated by Brown & Cumming (2009), yields $T_{\text{surf}} \sim 1.3 \times 10^8$ K. For such a core temperature, the minimum energy escaping the neutron star as neutrino’s (i.e. assuming standard core cooling) is $L_{\text{nu}} \sim 10^{34.35}$ erg s$^{-1}$ (Page et al. 2006).

Equating the energy losses via photon radiation from the neutron star surface ($L_{\gamma}$) and neutrino emissions from the stellar core ($L_{\nu}$) with the energy gained via crustal reactions during outburst ($L_{\text{acc}}$), suggests that EXO 0748–676 must have a time-averaged mass-accretion rate of $\langle M \rangle \gtrsim 8 \times 10^{15}$ g s$^{-1}$. During outburst, EXO 0748–676 displayed an average bolometric luminosity of $\sim 6 \times 10^{33}$ (D/7.4 kpc)$^2$ erg s$^{-1}$ (Sidoli et al. 2005; Boirin et al. 2007). Assuming that the accretion luminosity is given by $L_{\text{acc}} = (GM_\text{NS}/R_\text{NS})\langle M_{\text{BH}} \rangle$, this translates into a mass-accretion rate during outburst of $\langle M_{\text{BH}} \rangle \sim 3 \times 10^{15}$ g s$^{-1}$ for a canonical neutron star with $M = 1.4 M_\odot$ and $R = 10$ km.

If the crust has indeed thermally relaxed, the above estimates show that EXO 0748–676 must have a duty cycle of $\gtrsim 30$ per cent to explain the observed quiescent bolometric luminosity of $\sim 6 \times 10^{33}$ (D/7.4 kpc)$^2$ erg s$^{-1}$ in terms of thermal emission from the cooling neutron star (i.e. opposed to continued accretion). The outburst of EXO 0748–676 started between 1980 May and 1984 July and the system returned to quiescence in 2008 September, i.e. $t_{\text{ob}} = 24.28$ yr. If the observed outburst is typical for the long-term behaviour of this source, the expected recurrence time is thus $\lesssim 100$ yr. In case the neutron star cools via more efficient core neutrino emission processes, the recurrence time required to explain the observed quiescent luminosity is shorter (i.e. the duty cycle is higher). Although the above calculation is only a crude approximation (e.g. there is a significant uncertainty in the relation between the surface and interior temperature of the neutron star, depending on the atmospheric composition and the depth of the light element layer; Brown & Cumming 2009), it illustrates that EXO 0748–676 must have a high duty cycle if the cooling curve has indeed reached its quiescent base level.

Brown et al. (1998), Rutledge et al. (2000) and Colpi et al. (2001) have suggested that EXO 0748–676 continues to accrete in quiescence, because the quiescent luminosity inferred from the 1980 EINSTEIN observation is higher than predicted by standard cooling models. However, these conclusions are based on an assumed duty cycle of $\sim 1$ per cent, but we have no a priori knowledge about this. Although we cannot exclude that the system is indeed accreting in quiescence, the above estimates show that a duty cycle of $\gtrsim 30$ per cent can explain the observed quiescent level of EXO 0748–676 as being due to thermal emission from the cooling neutron star. A duty cycle of $\gtrsim 30$ per cent is high, although not unprecedented, for neutron star transients (e.g. Chen et al. 1997; Degenaar & Wijnands 2009).

Recently, Brown & Cumming (2009) demonstrated that the cooling of a neutron star crust is expected to follow a broken power-law decay. A break is predicted to occur due to a transition in the crystal structure of the crust matter, and the slope before the break reflects the heat flux from the outer crustal layers. Therefore, we also fitted the neutron star temperatures obtained for EXO 0748–676 to a power law and found decay indices of $-0.03 \pm 0.01$ and $-0.05 \pm 0.01$ for the Chandra and Swift data sets, respectively. The Swift observations indicate that a possible break in the quiescent light curve may have occurred $\sim \pm 265$ d after the cessation of the outburst (see Section 3.2). By fitting a broken power-law function, we obtain a decay index of $-0.03 \pm 0.03$ before the break, which steepens to $-0.06 \pm 0.02$ thereafter. However, since these slopes are consistent with being equal, further observations are required to confirm whether a break has indeed occurred.

The decay parameters that we find for EXO 0748–676 are comparable to that obtained by Fridriksson et al. (2010) for XTE J1701–462. These authors found that the quiescent light curve breaks $\sim \pm 20–150$ d post-outburst and report decay indices of $\sim -0.03$ and $\sim -0.07$ before and after the break, respectively. Fridriksson et al. (2010) note that possible cross-calibration effects between Chandra and XMM–Newton might introduce small shifts that also allow a single power-law decay with slope $\sim -0.05$. The cooling curves of KS 1731–260 and MXB 1659–29 appear to have steeper decays with indices of $\sim -0.12$ and $\sim -0.33$, respectively (Cackett et al. 2008). Due to the scarcity of data points it is unclear whether a break occurred in the quiescent light curves of the latter two sources (Cackett et al. 2008; Brown & Cumming 2009).

The power-law fits show no indications that the quiescent light curve of EXO 0748–676 is levelling off. Thus, it is also possible that the neutron star temperature continues to decay further and that the core is cooler than suggested by the exponential decay fits and the 1980 EINSTEIN detection. The relatively slow decrease of EXO 0748–676 might then reflect that the crust has a high conductivity, albeit lower than that of the neutron stars in KS 1731–260 and MXB 1659–29. Further observations are thus required to determine whether the neutron star crust in EXO 0748–676 has nearly cooled down and to be able to draw firm conclusions on the crust and core properties.

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3 We note that EXO 0748–676 is an eclipsing system and therefore part of the central X-ray flux may be intercepted from our line of sight. However, the X-ray burst behaviour of the source is consistent with the mass-accretion rate inferred from the observed X-ray luminosity (Boirin et al. 2007).
