Disappearance of quasi periodic-eruptions (QPEs) in GSN 069, simultaneous X-ray re-brightening, and predicted QPE re-appearance

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ABSTRACT

Aims. To present the short- and long-timescale properties of quasi-periodic eruptions (QPEs) in GSN 069 and its overall X-ray evolution in GSN 069 over the past 11 yr.

Methods. We study the timing and spectral properties of GSN 069 using 11 XMM-Newton and 1 Chandra observations from December 2010 to December 2021.

Results. QPEs are a transient phenomenon in GSN 069 last detected in January 2020 with a life-time between 1 yr and 5.5 yr. On short timescales, the QPE intensity and recurrence time oscillate defining alternating strong/weak QPEs and long/short recurrence times. The quiescent level variability in observations with QPEs exhibits a quasi-periodic oscillation (QPO) at the average observation-dependent recurrence time peaking with a delay of a few hr w.r.t. the preceding QPE. A significant late-time X-ray re-brightening starting with the QPE disappearance is observed in the long-term light curve of the quiescent emission, and the overall X-ray evolution follows the $L \propto T^4$ relation expected from constant-area blackbody emission.

Conclusions. QPEs in GSN 069 are consistent with being produced by successive tidal stripping events of a white dwarf (WD) donor in a highly eccentric orbit around the supermassive black hole, one QPE being produced at each pericenter passage. Our data suggest that the WD was partially disrupted when QPEs disappeared in GSN 069, giving rise to the X-ray re-brightening. We predict the re-appearance of QPEs in GSN 069 in the near future with different recurrence times than currently detected QPEs, as the surviving core will again suffer a series of tidal stripping events at pericenter passage.

Key words. Galaxies: nuclei — Galaxies: individual: GSN 069 — Accretion, accretion disks — Black Hole Physics — X-rays: individual: GSN 069

1. Introduction

GSN 069 was first detected in July 2010 during an XMM-Newton slew [Saxton et al. 2011] at a flux level more than a factor 240 above previous upper limits from ROSAT observations performed 16 years earlier. Subsequent observations with the Niel Gehrels Swift observatory show a relatively constant X-ray flux for the first ~1 yr [Miniutti et al. 2013], and further observations with Swift and XMM-Newton reveal a smooth flux decay during the following ~7-8 yr. This X-ray long-term evolution is best interpreted as the result of a tidal disruption event (TDE) whose extremely long-lived nature and UV spectral properties suggest the total or partial disruption of an evolved star [Shu et al. 2018; Sheng et al. 2021; MacLeod et al. 2012]. During an XMM-Newton X-ray observation on 24 December 2018, the X-ray light curve of GSN 069 exhibits high-amplitude, short-lived X-ray flares recurring every ~9 hr [Miniutti et al. 2019]. These quasi-periodic eruptions (QPEs) produce an increase of the X-ray count rate by up to two orders of magnitude in the hardest energy bands. They are characterized by thermal-like X-ray spectra with typical temperature of ~120 eV, superimposed to an otherwise stable quiescent level with $L \sim 50$ eV most likely due to the emission from the accretion disc resulting from the initial TDE.

Following the discovery of QPEs in GSN 069, this peculiar phenomenon has been observed in a handful of additional sources: RX J1301.9+2747 [Giustini et al. 2020], eRO-QPE1 and eRO-QPE2 [Arcodia et al. 2021], and most likely XMMSL1 J024916.6-041244 [Chakraborty et al. 2021]. So far, QPEs are consistent with being associated with TDE-like events produced by black holes of relatively small mass (of the order of $10^5-10^6$ $M_\odot$) as derived from a variety of different methods [Miniutti et al. 2019; Arcodia et al. 2021; Wevers et al. 2022]. None of the sources shows the broad optical emission lines that are associated with active nuclei, although the presence of a narrow line region (most evident in GSN 069), combined with the lack of any significant intrinsic absorption, suggests some level of past black hole activity [Miniutti et al. 2013; Wevers et al. 2022]. Recurrent X-ray flares sharing some common characteristics with QPEs have also been recently reported in the ultra-
luminous X-ray source XMMU J122939.7+075333 located in the globular cluster RZ 2109 in the Virgo galaxy NGC 4472 (Tiangco et al. 2022). Other sources that may perhaps be associated with the QPE phenomenon and/or variations of it are ESO 249-39 HLX-1 (Farrell et al. 2009; Godet et al. 2014) and ASASSN-14ko (Payne et al. 2021; Liu et al. 2022).

Several theoretical models have been considered to explain the QPE phenomenon. Proposed scenarios include (i) modified disc instability models (Sniegowska et al. 2020; Raj & Nixon 2021; Pan et al. 2022), (ii) gravitational lensing in a nearly equal-mass supermassive black hole binary (Ingram et al. 2021), (iii) mass transfer from one or more orbiting bodies in a variety of different configurations as discussed e.g. by King (2020, 2022), by Metzger et al. (2022), Zhao et al. (2022), and by Nixon & Coughlin (2022); Wang et al. (2022), or (iv) collisions between an orbiting secondary object and the accretion disc that is formed following the initial TDE (Suková et al. 2021; Xian et al. 2021).

In this work, we present results obtained from 12 pointed X-ray observations of GSN 069 (11 by XMM-Newton and 1 by Chandra) and we discuss the short- and long-timescale properties of both QPEs and continuum (quiescent) emission over the past 11 yr. Our results represent an important step in deriving observational constraints that can inform further theoretical work on the QPE formation process and subsequent evolution in GSN 069 as well as in the other QPE-sources discovered so far.

2. Observations and data analysis

GSN 069 was observed in the X-rays on several occasions with the XMM-Newton, Niel Gehrels Swift, and Chandra X-ray observatories. Pointed observations used in this work are reported in Table 1. Source and background products are extracted from circular regions on the same detector chip using the latest versions of the SAS (XMM-Newton) and CIAO (Chandra) dedicated software. X-ray light curves are background subtracted, as well as corrected for various effects (bad pixels, quantum efficiency, vignetting, dead time) using the SAS epiclccorr and CIAO dmextract dedicated tasks. All event files are barycenter-corrected in the DE405-ICRS reference system prior to analysis.

For XMM-Newton, we use here data from the EPIC-pn camera only for simplicity. Chandra data below 0.4 keV are ignored due to the severe contamination affecting the low-energy response of the ACIS detector. For this reason we do not use Chandra data in our spectral analysis as the X-ray emission in GSN 069 is super-soft.

3. The transient nature and properties of QPEs in GSN 069

Background-subtracted light curves from all observations with QPEs, i.e. from December 2018 (XMM3) to January 2020 (XMM6), are shown in Fig. 1 in a common 0.4-1 keV band. The Chandra light curve has been rescaled to match the XMM-Newton EPIC-pn effective area to better show the QPE intensity evolution regardless of the detector in use. QPEs are consistently detected from December 2018 (XMM3) to January 2020 (XMM6), although they appear much weaker and more irregularly spaced in the latter observation. No QPEs are detected during XMM2, a ∼ 92 ks XMM-Newton observation in December 2014, i.e. QPEs first appeared in GSN 069 sometime between December 2014 and December 2018. No clear QPEs are detected in an observation performed in May 2020 (XMM7) and subsequent observations. We hence conclude that QPEs in GSN 069 are a transient phenomenon with a life-time between ≃ 1 yr (XMM3 to XMM6) and ≃ 5.5 yr (XMM2 to XMM7).

We fit each 0.4-1 keV light curve with the simplest possible model comprising an observation-dependent constant C, representing the average quiescent level during each exposure, and a series of Gaussian functions with normalisation N and width σ describing QPEs. We define $T_{\text{rec}}$ as the time interval between the peak of two consecutive QPEs. The best-fitting results for all observations are reported in Table A.1. We point out that results are only valid in the 0.4-1 keV band, all quantities being energy-dependent as discussed by Minniti et al. (2019). In Fig. 2, we show the evolution of the QPE intensity, as measured from the best-fitting normalization of the Gaussian functions (see Table A.1), averaged over each observation. The QPE intensity decays monotonically decreasing by 0.22 cts s$^{-1}$ per 100 d in the 0.4-1 keV band. We also show the continuum level of the first observation with no QPEs (XMM7). If the decaying trend continued after XMM6, as appears likely, our ability to detect QPEs was seriously compromised already ≃ 20 d before the XMM7 observation.

As visually clear from Fig. 1 and quantitatively shown in Table A.1 the QPE intensity oscillates in long enough observations suggesting to define alternating strong and weak QPE types. The same is true for the recurrence time between QPEs, with strong (weak) QPEs being systematically followed by longer (shorter) recurrence times to the next QPE (with the exception of the more irregular XMM6 observation). The QPE intensity and recurrence time evolution during all observations comprising QPEs is shown in Fig. 3. The dashed lines are sine functions with period fixed at the observation-dependent averaged separation between QPEs of the same type (strong/weak), i.e. at about twice the averaged recurrence time between consecutive QPEs. As the difference between strong/weak QPE intensity...
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Fig. 1: XMM-Newton (EPIC-pn) and Chandra (ACIS-S) background-subtracted light curves from all observations with QPEs in a common 0.4-1 keV band. The Chandra light curve has been rescaled to the XMM-Newton pn effective area to better display the QPE amplitude evolution and to ease comparison between data from different observatories/detectors. We use time bins of 200 s and 500 s duration for XMM-Newton and Chandra data respectively. All panels have a common y-axis range.

Fig. 2: Time evolution of the QPE intensity since first detection. The QPE intensity is measured as the average of the best-fitting Gaussian normalization in each observation (i.e. we ignore here the difference between strong and weak QPEs) and associated standard deviation. The dashed line represents the best-fitting linear decay (corresponding to a decay of about 0.22 cts s$^{-1}$ per 100 d). We also show (cross) the continuum level during the first observation with no detected QPEs (XMM7). As discussed in Sect. 5, the continuum level of all observations with QPEs is lower, consistently with the detection of QPEs.

...sities and between long/short $T_{\text{rec}}$ decreases in all observations, we also impose an exponentially decaying amplitude of the sine functions. This signals that the intensity and recurrence time are likely modulated on a longer timescale and in a similar way. In fact, all exponential folding times are consistent with each other (although with very large uncertainties) and are of the order of 1 d. The dashed lines in Fig. 3 are not to be considered as actual fits; they are intended to guide the eye. We define $T_{\text{sum}}$ as the sum of two consecutive long/short recurrence times (or, equivalently, the separation between two QPEs of the same strong/weak type). We point out that $T_{\text{sum}}$ is not constant with time either, but appears to be modulated (or at least variable) on long timescales. Assuming that QPEs are present throughout between the XMM3 and XMM6 observations, $\sim$ 1,030 QPEs have been produced in that period of time. As mentioned above, however, QPE may have been present for longer, corresponding to $\sim$ 5,400 possible events.

Note the different behaviour during XMM6: while intensities still oscillate, they do so in a much less regular manner to the extent that it is difficult to unambiguously define the QPE type (especially for the first and last QPE). Most importantly, the recurrence time during XMM6 does not oscillate as in all other cases, but increases monotonically. As reported in Table A.1, the typical QPE duration, defined here arbitrarily as twice the best-fitting Gaussian FWHM is $\approx$ 3,780 s ($\approx$ 1.05 hr), and there is no clear difference between strong and weak QPEs duration, nor evident long-term evolution.

As per the long-term evolution of QPE intensities and recurrence times, Fig. 3 suggests that the contrast between strong/weak QPEs (e.g. the ratio between the intensity of consecutive QPEs) and the difference between the corresponding long/short consecutive recurrence times decrease together in observations long enough to provide a trend (XMM4 and XMM5). This is better shown in Fig. 4 where we plot the ratio between the intensity of consecutive QPEs as a function of the recurrence time between them. The recurrence time is shown as fraction of the average $T_{\text{sum}} = 64,423$ s (the sum of consecutive
1. The QPE intensity \(N\) for all observations with QPEs is shown in the upper panels. The recurrence time between consecutive QPEs is shown in the lower panels (each data point is placed at a time corresponding to half the separation between consecutive QPEs). The y-axis is always in the same range, except for the irregular XMM6 observation. Dashed lines in the XMM4, Chandra, and XMM5 panels are sine functions with period equal to twice the averaged, observation-dependent recurrence time, and with an exponentially decaying amplitude (with e-folding roughly consistent with \(\sim 1\) d in all cases) that most likely indicates a common long-term evolution of QPE intensities and recurrence times. The lines are intended to guide the eye rather than to provide fits the data.

2. In Fig. 3, the ratio between the intensity of consecutive QPEs is shown as a function of the associated recurrence time (normalized to the sum of consecutive long/short intervals \(T_{\text{sum}}\)). The horizontal line \((N_i / N_{i+1} = 1)\) separates events where strong QPEs precede weak ones (upper half of the Figure), from those where weak QPEs precede strong ones (lower half). The \(T_{\text{rec}} / T_{\text{sum}} = 0.5\) one separates short from long recurrence times. The two quantities appear to be correlated, although some significant scatter is present, and their best-fitting linear relation (dotted) crosses the intersection of the \(N_i / N_{i+1} = 1\) and \(T_{\text{rec}} / T_{\text{sum}} = 0.5\) lines exactly.

3. One long and one short recurrence times. The two quantities are well correlated, although significant scatter is present. Remarkably, the ratio between the intensity of consecutive QPEs is the same \((N_i / N_{i+1} = 1)\) when long and short recurrence times have equal duration \((T_{\text{rec}} / T_{\text{sum}} = 0.5)\), as shown by the intersection of the vertical and horizontal lines with the best-fitting linear relation. This configuration is never observed exactly, and is almost reached for the 3rd-4th QPEs during XMM4 when \(N_i / N_{i+1} = 1.18 \pm 0.07\) and \(T_{\text{rec}} / T_{\text{sum}} = 0.506 \pm 0.002\). The upper-left and lower-right quadrants in Fig. 3 are not populated. This means that (at least for the events that we have observed) long recurrence times always follow strong QPEs.

4. Quasi-periodic oscillation of the quiescent level (or secondary QPEs)

The statistical quality of the fits to the individual light curves with the simple constant plus Gaussian model is fair, but not excellent (see Table A.1). This is not due to inaccurate modeling of the QPE profiles, but rather to residual quiescent level variability. Visual inspection of the best-fitting residuals reveals that excess emission is systematically present \(\sim 10\) ks after most QPEs. As discussed in Sect. [B] and Fig. [B.1] and excluding the irregular XMM6 observation, the excess is quite clear after 9/12 of the QPEs observed with XMM-Newton (the Chandra data do not have sufficient quality to reveal variability of the quiescent level, as this is barely detected). In fact, the quiescent level appears to vary systematically with a characteristic timescale similar to the average observation-dependent recurrence time between consecutive QPEs, except during the XMM6 observation where excess emission is tentatively seen following QPEs, but with distinct properties (e.g. duration) with respect to all others (see Fig. [B.1]).

In order to search for systematic trends of the quiescent level variability with better signal-to-noise, we fold the light curves from the XMM3, XMM4, and XMM5 observations at the average observation-dependent recurrence time. We ignore the XMM6 observation whose increasing recurrence times prevent us from defining a clear folding timescale (see Fig. [3]). As Chandra data are ignored, there is no need to restrict the energy band above 0.4 keV, and we use the full 0.2-1 keV band in this analysis.
The 0.2-1 keV folded light curves are shown in the upper panels of Fig. 5 together with their best-fitting baseline (constant plus Gaussian) model. The middle panels show the resulting residual light curves where a sinusoidal trend is evident, strongly suggesting the presence of a quiescent level quasi-periodic oscillation (QPO) with period equal to the average observation-dependent recurrence time. Re-fitting the original folded light curves with the addition of a sine function (with period fixed at the folding timescale) improves very significantly the fits in all cases, and best-fitting residuals are shown in the lower panels. The best-fitting statistics for the model comprising the QPO provides and improvement of $\Delta \chi^2 = 134$ (XMM3), $\Delta \chi^2 = 302$ (XMM4), and $\Delta \chi^2 = 133$ (XMM5) for -2 degrees of freedom. The remaining residuals (see lower panel of Fig. 5) can be attributed to the fact that QPE profiles are not exactly Gaussian, especially once folded at the average recurrence time since the periodicity is not perfect and the folding process introduces small distortions.

We conclude that the QPO is highly significant in the folded light curves. Although deriving periodicity from arbitrarily folded light curves is not always robust, the extremely similar shape of the residual light curves makes it highly unlikely that the derived sinusoidal trend is spurious. The vertical lines in Fig. 5 mark the phase of the QPE (dotted) and of the peak of the QPO (dashed). Note that fits with the same statistical quality can be obtained by replacing the sine function with secondary QPEs described by weaker, broader Gaussian functions separated by one period. However, the level of the quiescent emission becomes negative in this case, which suggests to discard that solution (at least mathematically).

In Fig. 6 we show the time-evolution of the QPE intensity (here the average between strong and weak ones, as we fold on the recurrence time between consecutive QPEs) as well as of the ratio between the QPE and QPO best-fitting normalizations. The intensity of both QPEs and QPOs decays with time, but their ratio is consistent with being constant (and equal to $\sim 37.2$). The peak of the QPO emission lags the QPE by $8.3 \pm 0.3$ ks, $10.6 \pm 0.3$ ks, and $10.5 \pm 0.3$ ks in XMM3, XMM4, and XMM5 respectively. Although the number of data points is low, it is tempting to associate shorter time delays to observations with shorter recurrence times (the average recurrence time is 29757 s, 32151 s, and 32024 s during XMM3, XMM4, and XMM5 respectively). In fact, the delay and observation-dependent recurrence (folding) time appear to obey a 1:1 correlation, as shown in Fig. 7.

The detection of a quiescent level QPO with characteristic timescale of $\sim 9$ hr, equal to the average observation-dependent recurrence (folding) time suggests a QPO production mechanism linked to every single primary QPE regardless of their intrinsic type (strong or weak), and likely indicates that every pri-
primary QPE induces either an oscillation of the quiescent (disc) emission, or the production of a weaker and broader (longer-lasting) secondary QPE. A common production mechanism (or at least a link between the QPE and the QPO) is also suggested by their common time evolution which preserves their intensity ratio as well as by the 1:1 correlation between the QPO time delay (w.r.t. the primary QPE) and the observation-dependent recurrence time.

Note that a QPO of the quiescent level was also reported for another QPE-source, RX J1301.9+2747 by Song et al. (2020) in RX J1301.9+2747, the QPO is detected in two observations ~ 18.5 yr apart (both of which presenting X-ray QPEs), with a stable timescale of ~ 1 500 s. The QPO timescale in GSN 069 (~ 30-32 ks) and RX J1301.9+2747 (~ 1.5 ks) are remarkably different despite similar timescale for QPO recurrence times in the two sources (within a factor of 2) which may indicate a different production mechanism. In eRO-QPE1 no QPO is detected, although QPEs there are significantly more complex than in GSN 069 and it may be difficult to separate QPOs from multi-component QPEs (Arcodia et al. 2022). In eRO-QPE2, the quiescent level does not have high enough signal-to-noise to enable us to investigate the presence of any QPO in detail (Arcodia et al. in preparation).

5. The evolution of the quiescent level emission

Following first X-ray detection (July 2010), GSN 069 has been consistently detected in the soft X-rays. As discussed by Shu et al. (2018) and Miniutti et al. (2019) its X-ray flux evolution during the first ~ 9 yr shows a smooth flux decay by a factor of ~ 6-7 and is most likely consistent with a long-lived TDE. Such a long timescale with respect to the majority of observed X-ray TDEs, combined with the UV spectral properties of the source, strongly suggests the partial/total disruption of an evolved giant star (Miniutti et al. 2019; Sheng et al. 2021). Here we update the long-term X-ray flux light curve of GSN 069 presenting its evolution over the past ~ 11 yr using all available XMM-Newton pointed observations.

We extract spectra from the available 11 XMM-Newton observations excluding time intervals comprising QPEs, as our goal here is to present the evolution of the quiescent emission, most likely due to the accretion disc that is formed following the initial TDE. We assume a phenomenological model comprising (i) a thermal disc emission (the diskbb model in xspec) and (ii) a power law component, both at the redshift of GSN 069 (z = 0.0181). Most spectra also exhibit an absorption structure around 0.7 keV, first noted by Miniutti et al. (2013) in the XMM1 spectrum. Indeed, the feature is clearer in the XMM1 highest-flux observation, but appears likely present in all others as well. In order to check for the presence of a warm absorber also in the other observations, we first combine the X-ray spectra from different observations to increase signal-to-noise. In particular, we produce (i) a merged spectrum from all observations comprising QPEs (XMM3 to XMM6), and (ii) a merged spectrum from all other observations except XMM1 (where the feature is already clear), i.e. we merge the XMM2 spectrum with those from XMM7 to XMM11. As discussed below and shown in Fig. [10] the two merged spectra include observations with similar flux levels, so that the merged spectra are not dominated by one particular observation, but represent a reliable average in both cases.

We fit jointly the merged spectra with the spectral model defined above in the 0.3-1 keV band with Galactic column density fixed at $2.3 \times 10^{20}$ cm$^{-2}$, and $\Gamma = 1.9$ obtaining $\chi^2 = 942$ for 227 degrees of freedom. We then let the neutral column density free to vary but force it to be the same in both spectra, improving the fit to $\chi^2 = 405$ for 226 degrees of freedom, demonstrating that some absorption in excess of the Galactic is present. We then include a warm absorber model using a custom-build xstar grid (Kallman & Bautista 2001) that assumes a black body with kT= 50 eV as irradiating spectral energy distribution, as appro-
Fig. 8: Residuals (in terms of $\sigma$) when the merged XMM2 to XMM11 spectrum is fitted without (upper panel) and with (lower panel) a warm absorber component. The best-fitting model in the upper panel is associated with a column density in excess of the Galactic one, while this is fixed to the Galactic value in the lower panel where the excess absorption is accounted for by the warm absorber. We only show the most interesting energy range close to the absorption feature for better visual clarity.

Fig. 9: The intrinsic 0.2-2 keV $\text{diskbb}$ luminosity (as extrapolated from the spectral analysis in the 0.3-1 keV band) is plotted as a function of temperature for all 11 XMM-Newton observations. The dotted line is the best-fitting relation ($L \propto T^q$) resulting in $q = 4.1 \pm 0.3$.

| Energy (keV) | $\chi^2$ / $\nu$ = 2.00 |
|-------------|---------------------------|
| 0.5         | -4                        |
| 0.6         | -2                        |
| 0.7         | 0                         |
| 0.8         | 2                         |
| 0.9         | 4                         |
| 1.0         | 0                         |

| Energy (keV) | $\chi^2$ / $\nu$ = 1.25 |
|-------------|---------------------------|
| 0.5         | -4                        |
| 0.6         | -2                        |
| 0.7         | 0                         |
| 0.8         | 2                         |
| 0.9         | 4                         |
| 1.0         | 0                         |

We refrain from extrapolating our phenomenological model to much lower energies which would enable us to report the Bolometric luminosity evolution. Such an extrapolation is risky as we are only fitting the very high-energy tail of the black body emission using a rather phenomenological model. Moreover, TDE accretion discs are expected to be significantly smaller (in terms of gravitational radii) than in X-ray binaries or Active Galactic Nuclei, so that care should be taken not to significantly over-predict the optical/UV contribution. A much more detailed analysis of the spectral properties of GSN 069 will be presented in a forthcoming publication where the XMM-Newton EPIC-MOS and RGS data will be used, as well as the XMM-Newton Optical Monitor ones (corrected thanks to existing exposures with the Hubble Space Telescope) that will help us to
better constrain the broadband disc model. Such detailed analysis is beyond the scope of the present paper.

One of the most remarkable results of our analysis is the long-term evolution of the quiescent level X-ray flux of GSN 069. This is shown in the upper panel of Fig. 10 where the 0.3–1 keV observed X-ray flux is plotted as a function of time for the ~ 11 yr spanned by the XMM1 to XMM11 observations. The period during which QPEs are observed is highlighted (XMM3 to XMM6). GSN 069 was first detected 6 months prior to XMM1 during an XMM-Newton slew at a level that appears to be slightly higher than during XMM1, although consistent with it considering the associate large uncertainty. In the lower panel we show a zoom of the re-brightening phase with the number of the XMM-Newton observation indicated for reference (see Table 1).

6. Discussion

We first provide a summary of all results reported here and in previous studies of GSN 069 to inform the discussion. The body of results presented here is then used to constrain the different theoretical models that have been proposed so far for QPEs.

6.1. Summary of the main results

- The initial (~ 9 yr) X-ray flux evolution of GSN 069, especially when combined with the UV spectral properties, is consistent with a long-lived TDE likely resulting from the partial or total disruption of an evolved star (Shen et al. 2018). GSN 069 exhibits narrow optical emission lines, leading to an unambiguous Seyfert 2 classification, in optical spectra obtained both before and after the initial X-ray burst in July 2010. Optical spectra never show the broad optical emission lines associated with undergoing nuclear activity. The X-ray spectrum is never heavily absorbed, and the warm absorber parameters indicate that the absorber cannot obscure the broad line region. These results suggest that the central black hole was active in the past, leaving remnants narrow emission lines due to the extended size of the narrow line region, but has then switched off (Miniutti et al. 2013, 2019).

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QPEs in GSN 069 are abrupt flares occurring approximately every ~ 9 hr and lasting about ~ 1 hr during which the X-ray count rate increases by up to two orders of magnitude w.r.t. the quiescent level, depending on the considered energy band (Miniutti et al. 2019). They were first discovered in December 2018 and last detected in January 2020. QPEs are then a transient phenomenon in GSN 069 with life-time in the range of ~ 1 yr to ~ 5.5 yr. The QPE energy-dependence implies that QPEs are absent below ~ 0.1 keV (Miniutti et al. 2019). The average QPE intensity decays with time suggesting that they would have been undetectable against the quiescent level emission about 20 d before the XMM7 observation (the first one in which they are absent).

QPEs measured in high energy bands are stronger, peak earlier and have shorter duration than when measured at softer energies (Miniutti et al. 2019). However, as demonstrated by Arcodia et al. (2022) in the case of eRO-QPE1 (Arcodia et al. 2021), QPEs first rise in the softest energy bands, and the peak is reached first in the harder ones because of the much shorter duration of QPEs at high energies. This is difficult to confirm for GSN 069 because of the much shorter rise/decay timescale, but the trend appears to be consistent with GSN 069 as well, see Fig. 2 in [Miniutti et al. 2019].

With the exception of the last observation where they are detected (XMM6), QPEs are characterized by alternating long/short recurrence times and strong/weak intensity. Long recurrence times always follow strong QPEs. During the XMM6 observation, the alternating intensity is preserved, but recurrence times increase monotonically suggesting that the system was experiencing some major change, possibly associated with the lack of QPEs in subsequent observations (see Fig. 5). The contrast between strong/weak QPEs is correlated with the recurrence times as shown in Fig. 4 showing that strong QPEs are always followed by long recurrence times (and vice-versa). Remarkably, the correlation implies that strong/weak QPEs have the same intensity when long/short recurrence times have equal duration. Such configuration is approached but never exactly reached observationally.

During observations with QPEs, the quiescent level appears to vary with a characteristic timescale equal to the average observation-dependent recurrence time (see Fig. 5). Folded light curves exhibit a characteristic sinusoidal behaviour that is clear in the XM3, XM4, and XM5 observations, but not as evident in the irregular XMM6 one, where the increasing recurrence times prevent us from identifying an unambiguous folding timescale. The peak of the quiescent level QPO lags the preceding QPE by 8-10 ks, and the lag appears to define a 1:1 correlation with the average observation-dependent recurrence time. The ratio between the QPE and QPO intensities is observation-independent (i.e. constant with time) and equal to ~ 37 in the 0.2-1 keV band, suggesting a common production mechanism or a causal link between the two phenomena (Fig. 6 and 7).

The long-term X-ray flux evolution of the quiescent level over the past 11 yr follows approximately the $L \propto T^4$ relation expected if emission is due to a blackbody with constant area. Starting from the last observation during which (irregular) QPEs are detected, the X-ray emission of GSN 069, that was previously decaying as expected in a TDE-powered source, re-brightened significantly, reaching a second peak 10 – 11 yr after first X-ray detection (July 2010). The re-brightening peak is likely missed by our monitoring observations, but its 0.3-1 keV X-ray flux is $\geq 60\%$ of the first peak back in 2010. During the re-brightening phase the $L \propto T^4$ relation is preserved, although observations around the peak do not lie exactly on the relation, suggesting that the system is not in full equilibrium at peak

6.2. Constraints on QPE models

Classical disc instability models are difficult to reconcile with the fast recurrence time observed in GSN 069 for the given supermassive black hole (SMBH) mass of $\sim 4 \times 10^5 M_{\odot}$ (Miniutti et al. 2019) unless the disc properties are significantly different than standard as also discussed by Arcodia et al. (2021). Moreover, the alternating strong/weak QPEs and long/short recurrence time are not naturally predicted, and may need to be introduced by an ad hoc feedback mechanism. Also, instability-based models generally produce slow rise and fast decays, while QPEs in GSN 069 appear symmetric and, if anything, with a slower exponential decay at the highest energies as shown in Fig. 2 of Miniutti et al. (2019). However, modified models that significantly reduce the size of the unstable region and include disc-corona interaction and the presence of magnetic fields are worth exploring in the future (Sniegowska et al. 2020; Pan et al. 2022). As discussed by Arcodia et al. (2022), models based on pure gravitational lensing (Ingram et al. 2021) are disfavored due to the QPE energy-dependence (lensing being achromatic) and the difficulties in explaining simultaneously both the duration and amplitude of QPEs. Wang et al. (2022) have recently presented a model where QPEs are produced via mass transfer from a white dwarf (WD) donor in a WD-SMBH binary formed via the Hills mechanism. Within this scenario, a WD binary is captured and separated by the tidal field of the SMBH with one component being ejected and the other forming a highly eccentric binary with the SMBH. The varying tidal forces at pericenter passage can excite internal oscillation modes of the WD heating the envelope. The inflated envelope fills its Roche lobe and produces the initial TDE-like flare observed in 2010 in GSN 069, consistent with the abnormal C/N abundance derived from the UV spectrum by Sheng et al. (2021). The remaining WD core is left on a highly eccentric orbit which evolves under the competing effects of gravitational radiation, tidal forces, and mass transfer. After a few years, the surviving core also fills its Roche lobe at pericenter, and tidal stripping occurs with each mass transfer episode inducing a QPE in the X-rays by accretion onto the SMBH, likely mediated by the accretion disc formed after the first TDE-like event. The model thus provides a connection between the initial TDE-like event and the late-time appearance (a few years after the initial X-ray flash) of QPEs. At some point, the pericenter distance $R_p$ reaches the tidal radius $R_t$, and the WD is finally disrupted producing a second TDE-like event, in agreement with the X-ray re-brightening we observe.

Interestingly, Wang et al. (2022) estimate the QPE life-time for the parameters that best describe the light curve of GSN 069, i.e. the time between the start of the QPE phenomenon and the final disruption of the WD core occurring when $R_p \approx R_t$. The model predicts thousands of tidal stripping events (QPEs) and a total QPE life-time of ~ 1.2 yr in GSN 069, consistent with our observations. QPE disappearance and simultaneous X-ray re-brightening (i.e. the final TDE) are then also naturally linked.

Similar QPE life-times of years duration are estimated by Wang et al. (2022) for the other QPE sources. We point out, however, that QPEs have been observed in RX J301.9+2747 for the past 20 yr at least (Gustini et al. 2020). On the other hand, the donor may have different properties such as a much less massive
different ratio of initial $R_p/R_*$, and/or much lower WD rotation which may increase the QPE life-time to some extent. As discussed by Zhao et al. (2022) the donor may be an hydrogen-poor post-AGB star (producing a much longer QPE life-time of few thousand years) rather than a WD in some QPE sources, possibly explaining the diversity of QPE properties. It is also worth pointing out that QPEs in RX J301.9+2747 (and eRO-QPE1) appear to be much less regular than in GSN 069 (and eRO-QPE2) which suggests a different configuration in those systems.

In summary, the model proposed by Wang et al. (2022) for QPEs in GSN 069 appears highly successful in several aspects: it can explain the initial TDE-like flare (back in 2010) and the QPE late-time appearance (few years after the initial TDE-like event), the overall life-time of the QPE phenomenon in GSN 069, and it predicts the final disruption of the WD core at the end of the QPE phase, consistent with the X-ray re-brightening we observe simultaneously with the QPE disappearance.

However, Wang et al. (2022) do not address the alternating strong/weak QPEs and associated long/short recurrence times that were noted already by Miniutti et al. (2019) and that appear to be a defining characteristic of QPEs in GSN 069. On the other hand, this is adressed in a very similar QPE model proposed by King (2020) and also discussed by Chen et al. (2022). King (2022) points out that, due to the very fast mass transfer timescale in QPE sources (most likely significantly shorter than the hydrostatic timescale), the instantaneous mass transfer oscillates around its evolutionary mean, set by the angular momentum loss. An event with mass transfer above the evolutionary mean produces a strong QPEs and a long recurrence time to the next because the system widens slightly more than the WD can expand. The next QPE is necessarily weaker and associated with instantaneous mass transfer slightly below the evolutionary mean thus producing a weak QPE followed by a short recurrence time to the next (strong) one. This argument may then provide a viable mechanism to produce the observed alternating strong/weak QPEs and long/short recurrence times, although numerical simulations may be required to model in full detail the QPE light curves in the strong field regime of General Relativity. Within this context, strong QPEs are always followed by long recurrence times, as observed. Epochs when the instantaneous mass transfer is nerly equal to the evolutionary mean are then predicted to produce QPEs of very similar amplitude and recurrence times of nearly equal duration. The existence of such epochs, though never exactly observed, is fully consistent with our analysis, as shown in Fig. I. It appears therefore plausible/likely that a combination of the model proposed by Wang et al. (2022) with the theoretical arguments presented by King (2022) can successfully account for the most relevant properties of QPEs in GSN 069, as well as for the overall long-term X-ray evolution of the source, including the first TDE-like event in 2010, the appearance of QPEs a few (4.5-8.5) years later, and the X-ray re-brightening/QPE disappearance about 9-10 yr after the initial TDE-like event.

We point out that the WD highly eccentric orbit will inevitably precess on very short timescales, namely the pericenter precesses one full revolution in just a few orbits, or 0.5–1 d when assuming the system parameters in King (2022). Mass transfer events will then occur at points that have different distance and projected velocity w.r.t. a distant observer if the plane of the orbit is not exactly perpendicular to the line of sight (an occurrence associated with negligible probability). We then expect that QPE intensities and arrival times (or recurrence times) are modulated on the precession timescale. We are currently performing such an analysis on the long-enough observations (XMM4 and XMM5), and preliminary results indicate that the detection of such modulation is within reach of our data. Results from a detailed analysis will be presented in a forthcoming publication (Miniutti et al. in preparation).

An alternative attractive scenario that naturally explains the alternating long/short recurrence times is that of an initial partial TDE leaving a stellar core on a slightly eccentric orbit that impacts the accretion disc twice per orbit (Dai et al. 2010). A similar model, invoking impacts between a secondary orbiting black hole in a SMBH binary has been proposed to explain the apparent quasi-periodic optical outbursts in OJ 287 (Lehto & Vallonien 1996; Vallonien et al. 2003) and was also proposed as one of the possible explanations for the QPE phenomenon in Miniutti et al. (2019). As shown by Xian et al. (2021) such model can beautifully explain the irregularities of the QPE arrival times (and therefore recurrence times) in GSN 069 via the combination of a small eccentricity ($e = 0.05$) and relativistic precession (becoming 2$\pi$ after $\sim 259$ impacts, or $\sim 96$ d), once the appropriate light travel time effects in the curved SMBH spacetime are taken into account. Their orbital model successfully reproduces the QPE arrival times for an orbiter with semi-major axis $a = 365$ R$_*$ and small eccentricity ($e \approx 0.05$) crossing the accretion disc around a $3 \times 10^7$ M$_\odot$ SMBH twice per orbit. The derived SMBH mass is consistent with that derived by Miniutti et al. (2019) from X-ray spectral analysis. More work is needed to fully understand the X-ray emission process in the impacts scenario (Ivanov et al. 1998; Nayakshin et al. 2004; Suková et al. 2021). As per the connection with the initial TDE-like event in GSN 069, Xian et al. (2021) propose that the orbiter producing the impacts/QPEs is the remnant of a partial TDE of an evolved star. On the other hand, QPEs are observed with a significant time-delay with respect to the initial TDE-like event (4.5-8.5 yr), and this remains to be properly addressed within the impacts scenario. Xian et al. (2021) do not discuss the alternating strong/weak QPE pattern, nor its relation with alternating long/short recurrence times. In the star-disc collisions scenario, the QPE intensity may be related to (i) the absolute value of the star-disc relative velocity at impacts, or (ii) its projection onto the line-of-sight with impacts occurring towards the observer being brighter than those occurring in the opposite direction. In the former case (i), the largest contrast between strong and weak QPEs is reached when one impact occurs close to pericenter (high velocity) and the other far from it (low velocities) and this would produce nearly equal recurrence times, contrary to what is observed (see Fig. II). On the other hand, in case (ii) the observed behaviour is satisfied as the largest contrast between strong and weak QPEs is reached when both impacts are the closest to the pericenter, so that consecutive recurrence times have also maximal difference. We should however point out that precession implies that impacts towards the observer (i.e. strong QPEs in the latter case) will be followed by both long and short recurrence times depending on precession phase, contrary to what is observed.

Observations of other QPE sources with similar behavior to GSN 069, such as eRO-QPE2 (Arcodia et al. 2021, 2022), may help us obtaining better constraints both via detailed data analysis and orbital models fitting. One drawback of this model is that, while it can likely explain the regular QPE patterns observed in GSN 069 and eRO-QPE2, it appears difficult that it can provide the diversity that is needed to account for the less regular QPEs in RX J301.9+2747 and eRO-QPE1 (Giustini et al. 2020; Arcodia et al. 2022). Another potential problem is that the QPE lifetime is set by the drag force in each impact, leading to circular-
ization alignment of the orbital and disc planes on timescales of $\approx 1000$ yr way too long with respect to the observed 1-5.5 yr QPE phase life-time in GSN 069.

6.3. Quiescent level QPO

Proposed models should also account for the quiescent level QPO that we detect with a characteristic timescale equal to the average separation between consecutive QPEs (see Fig. 5). Disturbances in the accretion disc are naturally produced in both the mass transfer and impacts scenarios with a characteristic timescale set by the mass transfer episodes and/or consecutive impacts, in both cases $\approx 9$ hr as observed. In this context, the QPE-QPO time delay we measure is not necessarily relevant, as the QPO observed at a given epoch may be due to events having occurred long time before. On the other hand, the 1:1 correlation shown in Fig. 7 may suggest that the QPO (or secondary QPE) is indeed associated with the immediately preceding QPE. In the case of star-disc collisions, the perturbation needs however to propagate from the impact radial location (few hundreds $R_p = G M_{BH} c^{-2}$) to the X-ray emitting region (few tens $R_p$) in just 8-10 ks, corresponding to an exceedingly high propagation velocity in the accretion disc. In the mass transfer scenario, each pericenter passage disturbs the accretion disc and may create a precessing warped inner disc and/or oscillations (e.g. spiral waves) at the characteristic timescale of the orbital period. A warp is likely as the probability of perfect alignment between the orbital and disc planes is negligible.

6.4. X-ray re-brightening: a partial TDE leading to a new QPE phase?

As shown in Sect. 5 the QPE disappearance is associated with a significant X-ray re-brightening of GSN 069. The last observation with QPEs (XMM6) is also the first one in which an X-ray re-brightening is observed and shows monotonically increasing recurrence times instead of the previous quite regular alternation long/short separations. In the star-disc collision scenario, this may signal that the star was starting to break-up in several pieces, perhaps due to the 1 000-5 000 interactions with the disc. Debris may have then contributed to enhance the mass accretion rate onto the SMBH producing the X-ray re-brightening that is associated with QPE disappearance.

In mass transfer scenarios, the orbiting WD is, soon or later, predicted to finally disrupt (Wang et al. [2022]) which naturally associates the end of the QPE phase with the observed X-ray re-brightening. However, differently from the scenario outlined by Wang et al. [2022], we must point out that, as the WD approaches its tidal radius from above, the WD is most likely only partially rather than totally disrupted when $R_p \approx R_t$. Thus, we expect that a new, lower-mass degenerate core survives the partial disruption. Within this scenario, as shown in Fig. 10 (the partial TDE (pTDE) of the WD must have occurred sometime between the XMM5 (31 May 2019) and XMM6 (10 January 2020) observations. This can actually account for the puzzling monotonically increasing recurrence times during XMM6. At pTDE, an extreme mass transfer event from the low-mass donor to the SMBH (disc) takes place. The surviving remnant has to re-adjust to a new equilibrium on an hydrostatic timescale and, at the same time, the orbital period increases rapidly.

If our interpretation is correct, the surviving core will go through similar orbital evolution as the initial WD and, after reaching a new equilibrium configuration, will overfill its Roche lobe at some point giving rise to a new series of tidal stripping events producing a new series of QPEs. The new QPE phase will be characterized by different recurrence times than the previous one. According to Zalamea et al. [2010] and Wang et al. [2022] the initial evolution of the QPE phase is driven by the fact that mass transfer is initially weak, as the star barely touches its Roche lobe. This may therefore well be the reason why no clear QPEs are detected after XMM5. As the mass of the WD decreases, its radius expands and the WD overfills its Roche lobe more and more at each pericenter passage leading to higher mass loss and therefore stronger QPEs.

If the overall interpretation that we present here is correct, we then predict the re-appearance of relatively high-amplitude QPEs in GSN 069 in the near future. Note that since the system is initially still far from equilibrium, mass transfer is likely to occur far from the evolutionary mean which gives rise to a large contrast between consecutive strong and weak QPEs as well as a large difference between long and short recurrence times. The orbital period in this case will not be well approximated by any given recurrence time, but most likely by half the sum of consecutively long and short ones. Intense X-ray monitoring is needed not to loose the opportunity to observe the predicted new QPE phase. The subsequent evolution should be similar to the previous QPE phase that we have however observed only in its decaying phase (see Fig. 2). It is also possible that, at the end of this predicted second QPE phase, a second X-ray re-brightening occurs as the donor is again partially (or totally) disrupted. The system may in fact go through a series of QPE-phases followed by X-ray re-brightening events (pTDEs) until the donor is finally fully disrupted.

7. Conclusions

We present results obtained from the analysis of 11 XMM-Newton and 1 Chandra observations of GSN 069 over the past 11 yr. We show that QPEs are a transient phenomenon in GSN 069 first observed in December 2018 and last detected in January 2020 with an overall life-time between $\sim 1$ yr and $\sim 5.5$ yr. We show that the QPE intensity and recurrence time present an oscillatory behaviour with longer recurrence times systematically following stronger QPEs and vice-versa. The contrast between consecutive QPE amplitudes is correlated with the recurrence time suggesting that consecutive QPEs have equal amplitudes when recurrence time have equal duration. The quiescent level is characterized by a quasi-periodic oscillation with period equal to the average observation dependent recurrence time. The QPE peak lags the QPE by about 8-10 ks, and the QPE/QPO amplitude ratio is constant with time suggesting a causal link between the two phenomena. Simultaneously with QPE disappearance, the X-ray quiescence flux rapidly increases and reaches a peak around 10-11 yr after the initial TDE-like event (back in July 2010) with a flux that is $\geq 60\%$ of the initial TDE-like peak. The overall X-ray evolution in both the initial long-term decay and the rapid X-ray re-brightening following QPE disappearance is well described by the $L \propto T^4$ relation indicating that quiescent X-ray emission arises from an approximately constant-area blackbody emitter (most likely an accretion disc), consistent with its spectral shape at all epochs.

We point out that some low-significance short-lived flares are in fact present in some of the exposures after XMM6. These flares are weak, and likely consistent also with red-noise flickering. These apparent weak flares will be studied in detail in a forthcoming publication (Miniutti et al. in preparation).
The QPE properties, as well as the long-term X-ray evolution, are best understood within the following scenario (Wang et al. 2022; King 2022): a WD-WD binary is captured by the SMBH whose tidal forces eject one component, while the other forms a binary on a highly eccentric orbit with the SMBH. Time-varying tidal interactions excite the internal oscillation of the WD leading to heating and expansion of an envelope that overfills its Roche lobe producing a TDE-like event first observed in GSN 069 in July 2010. The X-ray emission, powered by accretion onto the SMBH, decays as in other X-ray TDEs. The surviving WD is still on a highly eccentric orbit that is shrinking due to energy and angular momentum losses and, after a few years from the initial TDE-like event, overfills its own Roche lobe at each pericenter passage. The consequent tidal stripping events produce the observed QPEs (one per each episode of mass transfer at pericenter). This QPE phase lasts for about 1 yr and ends when the pericenter finally reaches the WD tidal radius. We introduce a natural variation of this model (Wang et al. 2022) by pointing out that the WD is unlikely to be fully disrupted as the tidal radius is approached smoothly from larger pericenter distances. The disruption is hence most likely partial, and a lower-mass degenerate core survives. The pTDE produces the X-ray re-brightening we observe, and the period increase due to mass exchange from the low-mass donor to the high-mass SMBH leads to orbital evolution with increasing period, which explains the monotonically increasing recurrence times in the last observation where QPEs are observed (which is performed after the X-ray re-brightening begins, i.e. after pTDE).

The system is therefore entering a new QPE phase. Initially, QPEs are expected to be very weak, as the WD barely touches its Roche lobe (Zalamea et al. 2010), but QPE amplitudes are then expected to increase as the WD looses mass and expands filling more and more its Roche lobe at each pericenter passage. We then predict the re-appearance of (relatively) high-amplitude QPEs in GSN 069 in the near future with different recurrence time (orbital period) than in the previous phase. The subsequent evolution should be similar to the previous QPE phase with QPE intensities reaching a peak (not seen in the previous QPE phase) and then decreasing in time and possibly disappear again simultaneously with a new, second X-ray re-brightening. The system may actually go through a series of QPE-phases followed by X-ray re-brightening events (pTDEs) until the donor is finally fully disrupted. Future X-ray monitoring campaigns will reveal whether this scenario is confirmed or proved to be wrong.

We must also point out that, as the interaction basically only occurs at pericenter, QPEs in GSN 069 are an exceptional opportunity to probe the strong field regime of General Relativity (GR) in the immediate vicinity of a SMBH. In fact, for the reasonable set of parameters derived by King (2022) to describe the properties of the QPEs in GSN 069, the pericenter distance for the observed QPEs is likely of just a few $R_g$. The flash of X-ray emission at each pericenter passage thus represents a probe sending back to us a signal that can be accurately timed from a highly distorted region of spacetime. Further detailed data analysis of the QPE arrival times and of their energy/luminosity shifts may enable us to constrain the strong field regime of GR at distances from the SMBH event horizon that appears difficult to probe by other means.

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Appendix A: Tables

Appendix B: Quiescent level variability

In the upper panels of Fig. B.1 we show light curves from all XMM-Newton observations in which QPEs are observed. We ignore here the Chandra data as the quiescent level is barely detected there making it difficult to study its variability. As all data are from the XMM-Newton EPIC-pn detector, there is no need to restrict the analysis to energies above 0.4 keV, and we use here the 0.2-1 keV band. The light curves are modelled with a constant and a series of Gaussian functions describing the quiescence and QPEs respectively. The lower panels show the resulting residual light curves that have been rebinned for visual clarity to highlight relatively long-term variations (tens of ks timescales) of the quiescent level emission. In all cases but the XMM6 observation, the quiescent level exhibits broad excess emission following most QPEs, regardless of their strong/weak type. Excluding XMM6, an excess can be clearly seen after 9 out of 12 QPEs. The dashed and solid lines represent models describing the residual light curves either with a constant (dashed lines) or with an additional periodic function (solid lines) with period fixed at the average observation-dependent recurrence time between consecutive QPEs. Although the data are not very well described (especially in XMM5), the sinusoidal models represent a very significant improvement with respect to the constant one in all cases. In particular, re-fitting the original light curves with the addition of a sine function improves the statistical result by $\Delta \chi^2 = -114, -261, -63$ for the XMM3, XMM4, and XMM5 observations for $-2$ degrees of freedom, see Table A.1 for the statistical quality of the baseline model fits when the sine function is not included.
Table A.1: Best fitting parameters for fits to the 0.4–1 keV light curves from all observations with QPEs. We use time bins of 200 s and 500 s for XMM-Newton and Chandra observations respectively. Our model consists of an observation-dependent constant $C$ representing the quiescent count rate and a series of Gaussian functions with normalisation $N$ and width $\sigma$ describing the QPEs. Superscripts in the first column denote strong (s) and weak (w) QPEs respectively (see text for details). The separation between a QPE and the next ($T_{\text{rec}}$) and the QPE width ($\sigma$) are in units of seconds, while the quiescent level ($C$) and QPE intensity ($N$) are in cts s$^{-1}$. For each light curve, we also report the best-fitting $\chi^2$ and number of degrees of freedom. Errors represent the 1-$\sigma$ confidence intervals. The Chandra light curve has been rescaled to match the XMM-Newton EPIC-pn detector effective area prior to fitting (a factor of 36.775, see text for details). Hence the absolute values of $C$ and $N$ for that observation have to be taken with care.

\[
\begin{array}{cccccc}
T_{\text{rec}} & C & N & \sigma & \chi^2/\text{dof} \\
\hline
\text{XMM3} & & & & & 414/246 \\
\text{QPE}^{(w)} & 29757 \pm 34 & 0.046 \pm 0.001 & 0.96 \pm 0.04 & 810 \pm 25 \\
\text{QPE}^{(s)} & - & 1.37 \pm 0.04 & & 809 \pm 18 \\
\text{XMM4} & & & & & 875/644 \\
\text{QPE}^{(w)} & 33089 \pm 40 & 0.0451 \pm 0.0009 & 1.24 \pm 0.04 & 818 \pm 25 \\
\text{QPE}^{(s)} & 31266 \pm 37 & - & 0.87 \pm 0.03 & 817 \pm 23 \\
\text{QPE}^{(w)} & 32592 \pm 35 & - & 1.10 \pm 0.04 & 805 \pm 19 \\
\text{QPE}^{(w)} & 31656 \pm 35 & - & 0.93 \pm 0.04 & 800 \pm 22 \\
\text{QPE}^{(s)} & - & 1.22 \pm 0.04 & & 808 \pm 18 \\
\text{Chandra} & & & & & 14/61 \\
\text{QPE}^{(s)} & 33551 \pm 191 & 0.069 \pm 0.01 & 1.59 \pm 0.23 & 828 \pm 91 \\
\text{QPE}^{(w)} & 31865 \pm 211 & - & 0.81 \pm 0.17 & 757 \pm 119 \\
\text{QPE}^{(s)} & - & 1.06 \pm 0.19 & & 708 \pm 99 \\
\text{XMM5} & & & & & 867/636 \\
\text{QPE}^{(w)} & 30081 \pm 42 & 0.0242 \pm 0.0006 & 0.56 \pm 0.03 & 743 \pm 29 \\
\text{QPE}^{(s)} & 33458 \pm 38 & - & 0.93 \pm 0.04 & 810 \pm 22 \\
\text{QPE}^{(w)} & 31182 \pm 38 & - & 0.72 \pm 0.03 & 759 \pm 22 \\
\text{QPE}^{(s)} & 33373 \pm 41 & - & 0.89 \pm 0.03 & 831 \pm 21 \\
\text{QPE}^{(w)} & - & 0.76 \pm 0.03 & & 854 \pm 30 \\
\text{XMM6} & & & & & 745/634 \\
\text{QPE}^{(s)} & 26428 \pm 88 & 0.070 \pm 0.001 & 0.28 \pm 0.02 & 611 \pm 40 \\
\text{QPE}^{(w)} & 28794 \pm 88 & - & 0.22 \pm 0.02 & 749 \pm 52 \\
\text{QPE}^{(s)} & 35700 \pm 76 & - & 0.41 \pm 0.03 & 851 \pm 51 \\
\text{QPE}^{(w)} & - & 0.31 \pm 0.02 & & 744 \pm 50 \\
\end{array}
\]
Fig. B.1: In the upper panels, we show the 0.2-1 keV light curves from all XMM-Newton observations with QPEs, together with their best-fitting models comprising a constant and a series of Gaussian functions to describe the quiescent level and QPEs respectively. The lower panels show the corresponding residual light curves rebinned by a factor of 8, together with two models, namely a constant (dashed lines) and a sine function (solid lines) with period equal to the average observation-dependent recurrence time. The last XMM6 observation does not show clear signs of periodicity. Note that the recurrence times in XMM6 monotonically increase rather than presenting the usual long/short behaviour, and we omit the sine function in this case, although we note that some excess emission following QPEs is also seen (a long-duration event at the beginning of the observation which may follow a previous QPE, and two tentative shorter-duration flares following the second and third QPE).