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THE HUNT FOR QUASI-PERIODIC ERUPTIONS

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Abstract. Quasi-Periodic Eruptions (QPEs) are the latest addition to the ever-growing family of extra-galactic transients. The first QPE source was discovered in 2019, with a current total of four known sources (with two additional candidates). From an observational standpoint, they appear as repeated ∼2h-long bright bursts of thermal X-rays, with a regular quasi-periodic pattern between peaks in most of them (but not all). They appear to be linked to Tidal Disruption Events (TDEs, when an inbound star gets disrupted by the tidal forces of a Super-Massive Black Hole). Several models have been suggested, trying to account for the complex observed behaviour of these puzzling objects, but they all fall short in some aspects. Understanding these peculiar objects might help us constrain the physics of super-Eddington accretion (that happens in both TDEs and QPEs), and thus the growth of Super-Massive Black Holes. I summarize here the current state of the art of the study of QPEs, and its most recent developments. I present a new QPE candidate, Tormund, that was found as part of a larger endeavour aimed at data-mining the current and past multi-instrument X-ray archives to unearth previously-undetected transient events.

Keywords: galaxies: nuclei - accretion, accretion disks - black hole physics

1 Introduction

One of the current open questions in astrophysics is that of the growth of Super-Massive Black Holes (SMBHs). The very existence of SMBHs with $M_{BH} >\sim 10^9 M_\odot$ at redshift $z >\sim 6$ (when the Universe was less than one billion years old), as revealed by the detection of luminous very high-z quasars (e.g. Wang et al. 2021), challenges theoretical models for early BH formation and evolution as it appears difficult to reach such high masses in such a short timescale (e.g. Volonteri 2010). The proposed scenarios include intermediate-mass black hole (IMBH, in the $\sim 10^2$-$10^5 M_\odot$ range) progenitors continously accreting at their Eddington rate (i.e. the maximum rate for standard accretion models), or less massive seeds experiencing shorter-lived super-Eddington accretion events. Mergers could also play an important role (see e.g. Volonteri et al. 2021, for a review). From an observational point of view, future space-based gravitational wave observatories are needed to detect SMBH binaries leading to mergers and, at present, we need to rely on electromagnetic observations to make progress in the field of SMBH growth and evolution. As such, increasing the sample size of super-Eddington accretors can be of paramount importance to deepen our understanding of SMBH growth and evolution.

There are various astrophysical objects that can exhibit super-Eddington accretion. One of these are Tidal Disruption Events (TDEs, e.g. Gezari 2021). TDEs correspond to the destruction of a star by a massive black hole due to the tidal forces. This results in orbiting stellar debris, that create a temporary accretion disc around the super-massive black hole (SMBH). This then leads to a transient outburst, lasting several months, reaching super-Eddington levels. While TDEs are being intensely studied, the precise phenomena at play are still somewhat unclear. One seemingly independent phenomenon could help us understand TDEs: quasi-periodic eruptions (QPEs).

2 Our current understanding of QPEs

QPEs were first discovered in 2019 in GSN 069(Miniutti et al. 2019). To date, only four bona fide QPE sources are known, with one strong candidate. These sources are characterised by intense bursts of soft X-rays, lasting

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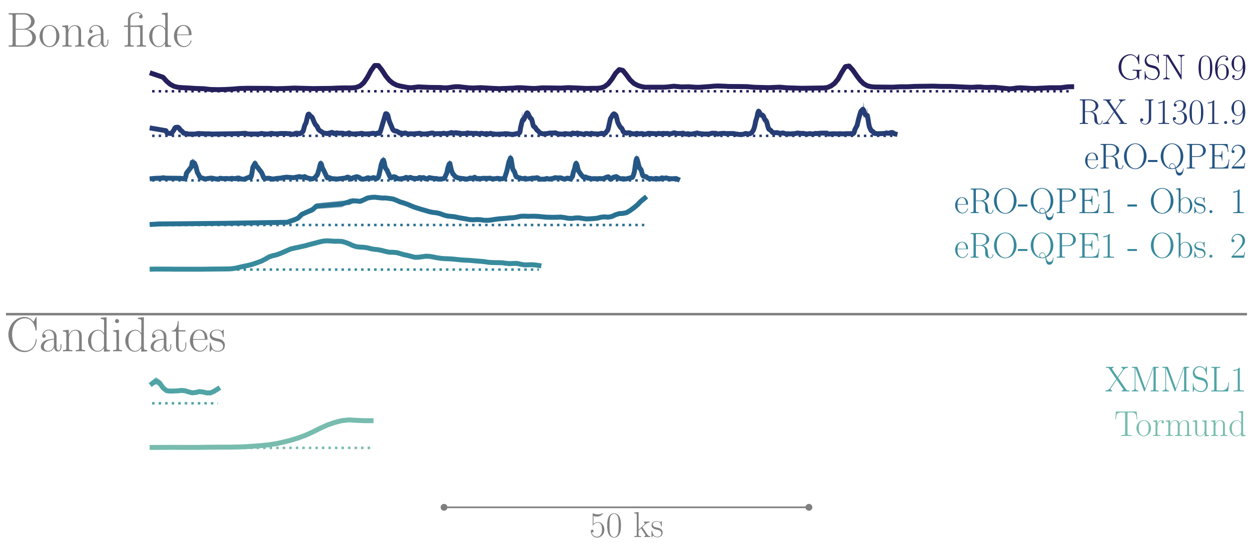

Fig. 1. Qualitative overview of the difference in the shape of the *XMM-Newton* 0.2–2 keV lightcurves of the known QPE bona fide sources (top) and candidates (bottom) (Miniutti et al. 2019; Giustini et al. 2020; Arcodia et al. 2021; Chakraborty et al. 2021; Quintin et al. 2023). The lightcurves are normalized by their respective peak count-rate value, to allow comparison of their shapes. The time axis is common to all lightcurves, with the scale shown at the bottom. The first observation of eRO-QPE1 finished with a large amplitude burst that was cropped here for visualization purposes - it reached about 5 times higher than the previous peaks of the same observation.

about an hour and repeating every few hours, showing thermal emission with temperatures of $\sim$ 50 eV in quiescence, and reaching $\sim$100 eV at the peak. These peaks can repeat in regular or irregular patterns. They are transient on longer timescales, for example the QPEs in GSN 069 being observed over the course of $\sim$1 year only, then disappearing with a rebrightening of the quiescent state, and finally appearing again a few months later with a different pulse profile (Miniutti et al. 2023a,b). Finally, QPEs appear observationally correlated with TDEs. Out of the five known QPEs, two show a link with past X-ray TDEs. This is unlikely to be a coincidence considering the rarity of TDEs (rate of $\sim 6\times10^{-5}$ yr^{-1} galaxy^{-1}, van Velzen et al. 2020).

The precise phenomena at play in QPEs are still unclear, and several models have been suggested to explain their properties. They all try to encompass the observational link with TDEs. The first type of model is based on different sorts of instabilities in the transient accretion flow from a TDE (e.g. Śniegowska et al. 2023). The second type of model uses a partial TDE, with a remaining body orbiting the black hole and interacting with the disk (e.g. Franchini et al. 2023). The last type of model corresponds to repeated tidal strippings of an orbiting white dwarf (e.g. Wang et al. 2022). Intense monitoring of the known sources, as well as additional detections and observations of new QPEs are necessary to discriminate between the models and understand the nature of QPEs. With this aim, and as part of an ongoing study on the systematic exploitation of multi-instrument X-ray archives, we searched for new QPE candidates previously missed in archival data.

3 Tormund: a new QPE candidate

3.1 Data mining

This search for QPEs is a part of a larger endeavour, part of the XMM2Athena project (Webb et al. 2023), which aims at making full use of the archival X-ray data (see Quintin et al. to be sub. for details). The general idea is that the best way to reveal the long-term variability of an object is to sample its evolution as intensively as possible. For this purpose, we cross-matched the largest available X-ray catalogs, and systematically computed the XMM-Newton upper limits for all non-XMM sources that lay in the XMM-Newton observational footprint. This led to a catalog of $\sim$ 1M X-ray sources, that has two applications. First, we can compare any new XMM-Newton detection to the archival data, allowing to automatically detect transient events. This is the STONKS pipeline, that is currently being embedded in the XMM-Newton pipeline (Quintin et al. to be sub.). The second application is that we can directly data mine the catalog in search of objects of interest, using the available properties. This was used for instance to find a new candidate pulsating ultra-luminous X-ray source (another type of super-Eddington accretor) through its long-term variability (Quintin et al. 2021).

In order to find QPEs, we looked for short-term variable, soft X-ray sources for which the position matched the centre of galaxies present in the GLADE+ catalogue (Dálya et al. 2022). This allowed us to detect known QPEs (which confirms the efficiency of the method), and a new QPE candidate, 4XMM J123856.3+330957.

3.2 Tormund's properties

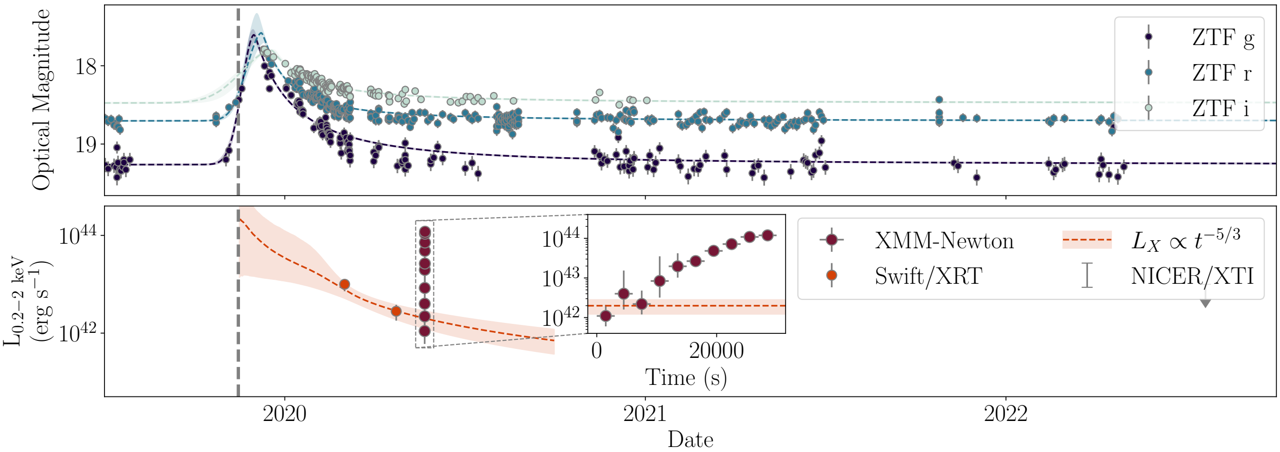

Fig. 2. Long-term lightcurves of AT 2019vcb, nicknamed Tormund (extracted from Quintin et al. 2023). *Top panel:* ZTF monitoring of the source, showing the optical TDE in the g, r and i bands. *Bottom panel:* X-ray long-term lightcurve of Tormund, with the inset showing the short-term eruption during the XMM-Newton observation. The orange dashed line and shaded region correpond to the confidence region of a $\propto t^{-5/3}$ X-ray decay using only the two Swift data points, showing that the beginning of the XMM-Newton observation is consistent with this expected behaviour.

The full details of the study of this object are presented in Quintin et al. (2023). This source was originally detected as an optical transient event: AT 2019vcb. It was observed first by the Zwicky Transient Facility (ZTF, Bellm 2014) on November 15, 2019 (ZTF19acspeuw, nicknamed Tormund), and then by ATLAS (ATLAS19bcyz) and Gaia (Gaia19feb) a few days later. With an amplitude of ∼1 magnitude and a decay over about 100 days, it was classified as a TDE. Such a discovery led to two follow-ups: an optical spectrum, that allowed to confirm its TDE nature and revealed numerous broad emission lines, consistent with a H+He TDE (see Fig. 1 in Hammerstein et al. 2022). Using the `MOSFiT` TDE model (Guillochon et al. 2018), the black hole mass was also estimated at $M_{\mathrm{BH}} \approx 8.3^{+0.8}_{-0.7} \times 10^7\ \mathrm{M}_\odot$. The second follow-up was in X-rays, with two Swift exposures and one by XMM-Newton. The Swift data points and the beginning of the XMM-Newton observation are consistent with the expected $F_X \propto t^{-5/3}$ emission (see envelope in Fig. 2), with a soft thermal emission. However, in the second half of the XMM-Newton observation, the source underwent an extreme rebrightening.

In less than 15ks, the source luminosity increased from $\sim 3\times10^{42}$ erg s^{-1} to $\sim 10^{44}$ erg s^{-1}, and its temperature rose from ∼50 eV to ∼120 eV. This behaviour is similar to the other known long-timescale QPE source, eRO-QPE1 (Arcodia et al. 2022) – with the exception that the short duration of the observation prevented from observing an entire flare. A late optical spectral follow-up, once the TDE was over, allowed to rule out the presence of an AGN that could have powered this variability. Such variability amplitudes and timescales are not expected from X-ray TDEs, which show fairly steady decay with mild short-term variability (typically factors of ∼5 in ∼days). As a consequence, we argued that Tormund was a strong QPE candidate.

3.3 Consequences on QPE models

As a strong QPE candidate, the existence of this source has several consequences on our understanding of QPEs in general:

- This source is the third QPE source which is associated with a TDE, bringing the fraction of TDE-linked QPE to three out of five. This allows to definitely exclude the hypothesis that this correlation is fortuitous, and confirms the need to account for an initial TDE in the QPE formation models

- This is the first QPE source for which the initial TDE was detected in visible light, and thus for which the time of disruption could be precisely constrained (as opposed to deduced from variability from anterior archival flux values, for the other two sources). This allows in turn to put constraints on the formation time of QPEs, which must be below 6 months. This is remarkably short for models that require a circularization of a remnant through emission of gravitational waves, which should require longer formation times.
- This QPE is the brightest (both in terms of quiescent and peak flux), has the longest rise timescale, and the largest black hole mass of the known sample. This is puzzling, as such a scaling does not seem to exist in TDEs (Gezari 2021), and might thus provide us insight on the different physical mechanisms at play.

4 Conclusions

The study of QPEs is a very recent field, and a lot is still yet to be understood. Systematic and in-depth exploitation of the archives may allow us to discover more of these rare objects, and intense multi-wavelength long-term monitoring of the few that are known is necessary. As they seem to provide an *in-situ* probe of the inner accretion-powered engine of TDEs, understanding them might give us the keys to understand TDEs, and thus constrain super-Eddington accretion models.

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