A 200-Second Quasi-Periodicity After the Tidal Disruption of a Star by a Dormant Black Hole

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Supermassive black holes (SMBHs; $M \gtrsim 10^5\ M_\odot$) are known to exist at the center of most galaxies with sufficient stellar mass. In the local Universe, it is possible to infer their properties from the surrounding stars or gas. However, at high redshifts we require active, continuous accretion to infer the presence of the SMBHs, often coming in the form of long-term accretion in active galactic nuclei. SMBHs can also capture and tidally disrupt stars orbiting nearby, resulting in bright flares from otherwise quiescent black holes. Here, we report on a ~200-s X-ray quasi-periodicity around a previously dormant SMBH located in the center of a galaxy at redshift z = 0.3534. This result may open the possibility of probing general relativity beyond our local Universe.

Tidal disruption of stars as a means to fuel active SMBHs was originally proposed in 1975 (*1*) but it was not until over a decade later that the possibility of using the expected electromagnetic flares to study non-active SMBHs was proposed (*2*). Since then, various candidate tidal disruption flares (TDFs) have been identified based on luminous flares observed from optical to X-rays (*3–7*), but it is only in recent years that such objects have been confirmed through the observation of relativistic flares (*8–12*).

Swift J164449.3+573451 (hereafter Sw J1644+57) was detected (*8*) by the *Swift* Burst Alert Telescope (BAT, 15-150 keV) on 28 March 2011 as it reached X-ray luminosities greater than ~ 10^{48} erg s^{-1}. Prompt, multi-wavelength observations spanning from radio to γ-rays (*9, 11*) confirmed the position of the source to be coincidental with the nucleus of an inactive galaxy and showed the presence of rapid time variability ($\approx 10^2$ s) at high energies (*8, 10*), indicative of a highly compact source of emission (~30 million km or ~0.2 AU). Furthermore, the detection of a relativistic and highly collimated radio jet, for the first time associated with a TDF (*10, 11*), makes Sw J1644+57 analogous to a small-scale blazar (*10*). Following the identification of this source as a tidal disruption candidate (TDC), we initiated a series of twelve, bi-weekly observations with the large X-ray satellite *XMM-Newton*, starting approximately 19 days after the BAT trigger (Fig. 1), together with a further *Suzaku* pointing ~ 10 days earlier (*13*). The long-term evolution in the X-ray (0.2-10 keV; observed frame) luminosity followed roughly the expected rate of mass return to the black hole [$\propto t^{-5/3}$ for TDFs (*2*)] and the short-term, rapid variability was also apparent.

We produced light curves for all observations of Sw J1644+57 over the 0.2-10.0 keV energy band and Fourier transformed these in order to obtain various power density spectra. A least-squares fits to the soft energy band (<2 keV) power spectrum for the *Suzaku* observation is consistent with a band-limited (red) noise component, described by a $\Gamma \approx -1.8$ power-law plus Poisson (white) noise (fig. S1 and table S1). However, the 2-10 keV power spectra of both the *Suzaku* and first *XMM-Newton* observations (hereafter *XMM* #1) displayed a potential Quasi-Periodic Oscillation (QPO) component near 5mHz (Fig. 2). This feature has a centroid frequency of $\nu \sim 4.8$ mHz and frequency width (full-width at half-maximum) of $\delta\nu_{\rm suzaku} \leq 0.4$ mHz and $\delta\nu_{\rm xmm}$=0.3 mHz (quality factor $Q = \nu/\delta\nu \geq 12$ and ~ 15 for *Suzaku* and *XMM* #1 respectively). The fractional root-mean-square (r.m.s.) variability in the QPO is ≥2.8% and ~4% for *Suzaku* and *XMM* #1, respectively (fig. S2).

Assuming the signal is on top of a purely Poisson-noise time series, the limit on the r.m.s. variability found here results (*14*) in a single-trial significance in the Gaussian limit of 3.8σ for *Suzaku* and 2.2σ for *XMM* #1. However, in order to rigorously quantify the strength of the signal outside of the Gaussian regime and fully account for the presence of missing and unequally spaced data (Fig. 1), we conducted Monte Carlo simulations. The method we adopted is based on well established procedures in timing studies of compact objects (*14–16*). A series of 50,000 light-curves with the same average intensity, standard deviation, and number of bins as the original data were produced, and the noise power distribution was found at all Fourier frequencies and compared to the real observations (fig. S4). In this manner, we found that the chance that the individual detections at ~ 5 mHz are due to random noise to be $P_{false|suzaku}$= 1.4 × 10^{-4} and $P_{false|xmm}$ < 5 × 10^{-4} for *Suzaku* and *XMM* #1 respectively (fig. S7). After correcting for the initial "blind-search" of the *Suzaku* data and accounting for the fact that the QPO was detected in two independent observations, with different telescopes, the probability of two chance 3σ detections arising from random noise alone was found to be 1.52×10^{-5}. The observed quasi-periodic signal at ~ 5 mHz in Sw J1644+57 is statistically highly significant (4.33σ assuming Gaussianity in the probability).

QPOs are regularly seen in stellar mass black holes. Recently, QPOs have also been observed in a single AGN (*17*), and in a couple of potential intermediate-mass black holes (~ $10^3\ M_\odot$) (*18, 19*). Despite the lack of a unique physical explanation, most models (*20–24*) strongly link the origin of QPOs with orbits and/or resonances in the inner accretion disc close to the black hole. The detection of a QPO approximately 10 days after Sw J1644+57 became active requires that an accretion disc was formed shortly after the start of the initial TDF. The characteristic time (*2, 25*), $t_{\rm fall}$, it takes for material from the disrupted star to fall back toward the black hole in Sw J1644+57 from a pericenter distance of $R_p \sim 13(M_{\rm BH}/10^6\ M_\odot)^{-5/6}\ R_{\rm S}$ (*11*) (where the Schwarzschild radius $R_{\rm S} = 2GM/c^2$) is $t_{\rm fall} \approx 1$ day. This is consistent with the formation of an accretion disc due to stream-stream collision (*2*) after a small multiple of the $t_{\rm fall}$. The Keplerian frequency at the radius of the innermost stable circular orbit (ISCO = $0.5 - 3R_{\rm S}$, depending on whether the black hole is spinning or not), just short of the black hole's event horizon, is generally the highest characteristic variability frequency. If the 5 mHz QPO centroid frequency is set by orbits at the ISCO, it would imply a black hole mass between ~ 4.5×10^5 and $5 \times 10^6\ M_\odot$ - for a non-rotating and maximally rotating black hole, respectively. This is in line with predictions based on simultaneous X-ray and radio observations (*26*) (~ $3.2 \times 10^5\ M_\odot$) as well as the upper limit imposed by the M–L relation (<$2 \times 10^7\ M_\odot$) (*8, 10*). Keplerian frequencies at the ISCO scale inversely with black hole mass; assuming a $\sim 10^6 M_\odot$ black hole, the $\sim$ 5 mHz QPO would correspond to a frequency of $\sim$ 500 Hz around a $\sim 10 M_\odot$ black hole. This is remarkably similar to the 450 Hz oscillation found for GRO J1655-40 (*27*). Our results thus confirms a fundamental aspect of disc/disruption theory (*2*) and highlights the scale invariant nature (*28–31*) of the underlying physics governing the accretion flow onto supermassive ($\sim 10^{5-9} M_\odot$) and stellar-mass ($\sim 10 M_\odot$) black holes, several of which have displayed similar X-ray periodicities (*32*).

Moreover, the Eddington limit for this black hole is $<6 \times 10^{44}$ erg s^{-1}, making the peak luminosity where the QPO is observed highly super-Eddington (Fig. 1). Thus, quasi-periodicities should be preserved in not only mildly super-Eddington accretion flows, as is the case for the only other supermassive black hole RE J1034+396 (*17, 33*) showing a QPO, and the stellar-mass black hole GRS 1915+105 (*34*), but also in potentially highly beamed, anisotropic sources. Recent numerical simulations have began to examine the role of relativistic jets in the production of QPOs (*24, 35*), however, even in this scenario, it is the connection between the accretion disk and the base of the jet that give rise to the quasi- periodic signal.

Although we have drawn from a rich literature that has ensured a high standard of robust techniques, there is still the concern that other uncertainties in the theoretical framework of accretion flows could be at play and result in unaccounted systematic errors in the absolute noise model around black holes. Noise may not be purely white, purely red or a simple combination of the two, resulting in a smooth, featureless continuum. Indeed, (*36*), using general relativistic, magnetohydrodynamic simulations of the accretion flow onto a Schwarzschild black hole showed possible high frequency quasi-periodic features which were identified with properties of the turbulent flow. If this turns out to be the general case, QPOs similar to the one detected here would still be highly useful in determining the physics of the accretion flow, but might not be trivially related to the fundamental properties of the black hole, i.e., mass and spin.

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Supplementary Materials

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Materials and Methods
Figs. S1 to S9
Table S1
References (*37–56*)

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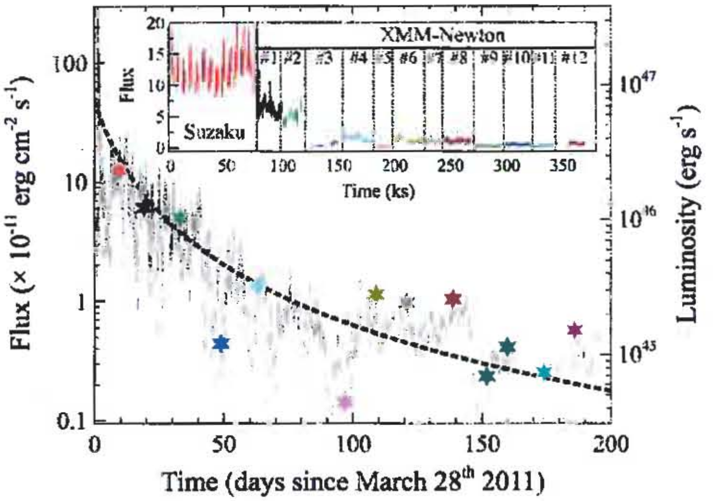

Fig. 1. *XMM-Newton* and *Suzaku* light curve of Sw J1644+57 together with the *SWIFT*-XRT 0.3-10 keV light curve for reference (grey) (*37*, *38*). For twelve *XMM-Newton* observations (*XMM* #1-12) we extracted 0.2-10 keV source and background light curves from the PN camera, using 40-arcsec circular regions. After accounting for the flaring background, a substantial fraction of the data in *XMM* #2, 3 and 12 had to be excluded. For *Suzaku*, we used a box region of 250-arcsec to extract the source light-curve from the two front-illuminated cameras and 150-arcsec for the background. Every observation had a background level significantly less than 5% of the total flux. For each observation we created an energy spectrum to which we fitted a model consisting of an absorbed power-law and used this to obtain a conversion factor between the count-rate and fluxes in physical units. The average flux levels in each observation are shown in real time in the main axis (stars, where the one s.d. error bars are smaller than the symbol size) and the inset compares each observation with data points binned in 32-s intervals. The vertical lines separate the various observations. The right-hand axis gives the conversion to luminosity of the source assuming isotropic radiation and the dashed curve shows a $t^{-5/3}$ relation with t being the time since March 28 2011.

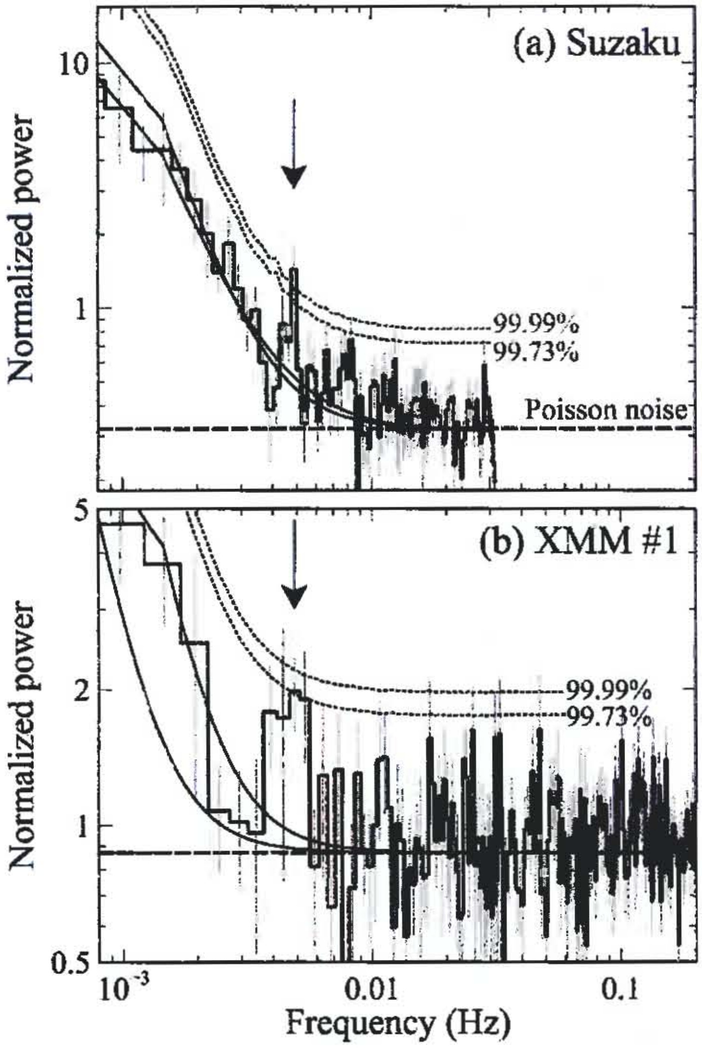

Fig. 2. (**A**) Power spectra for *Suzaku* and (**B**) for *XMM* #1, in the 2-10 keV energy range. The power spectra are normalised such that their integral gives the squared r.m.s. fractional variability. The Poisson noise level expected from the data errors is shown as the dashed horizontal line. We checked that the peak is robust to a variety of frequency and time resolutions. The arrow in both panels mark the presence of a QPO with a centroid frequency of $\nu_{\rm suzaku}$ ~ 4.8 mHz. The solid curves enclose the range of the best fit to the underlying continuum as described in Table S1 (Model 2). The dotted curves show the 99.99% and 99.73% (3σ) threshold for significant detection.