Discovery of thermonuclear (Type I) X-ray bursts in the X-ray binary Swift J1858.6–0814 observed with NICER and NuSTAR

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ABSTRACT
Swift J1858.6–0814 is a recently discovered X-ray binary notable for extremely strong variability (by factors of >100 in soft X-rays) in its discovery state. We present the detection of five thermonuclear (Type I) X-ray bursts from Swift J1858.6–0814, implying that the compact object in the system is a neutron star (NS). Some of the bursts show photospheric radius expansion, so their peak flux can be used to estimate the distance to the system. The peak luminosity, and hence distance, can depend on several system parameters; for the most likely values, a high inclination and a helium atmosphere, $D = 12.8 ^{+0.8}_{-0.6}$ kpc, although systematic effects allow a conservative range of 9–18 kpc. Before one burst, we detect a QPO at 9.6 ± 0.5 mHz with a fractional rms amplitude of 2.2 ± 0.2 per cent (0.5–10 keV), likely due to marginally stable burning of helium; similar oscillations may be present before the other bursts but the light curves are not long enough to allow their detection. We also search for burst oscillations but do not detect any, with an upper limit in the best case of 15 per cent fractional amplitude (over 1–8 keV). Finally, we discuss the implications of the NS accretor and this distance on other inferences which have been made about the system. In particular, we find that Swift J1858.6–0814 was observed at super-Eddington luminosities at least during bright flares during the variable stage of its outburst.

Key words: accretion, accretion discs – stars: neutron – X-rays: binaries – X-rays: bursts.

1 INTRODUCTION
A key aspect of accreting systems is the object on to which the accretion is occurring; in X-ray binaries (XRBs), this is either a neutron star (NS) or black hole (BH). Many observable properties are similar in either case, so determining which is present is often a challenging task.

There are several properties, which can divide NSs and BHs as populations and some features, which empirically appear to occur in only one type of system. First, outbursts of the different classes of source follow different tracks in gross properties such as the hardness–intensity or colour–colour diagrams (e.g. van der Klis 2006). However, this requires monitoring of the full outburst and some sources do not follow the typical patterns. Additionally, quasi-periodic oscillations (QPOs) are only found at kHz frequencies in NS systems (Strohmayer et al. 1996; van der Klis et al. 1996), although there is not yet a universally accepted model for their production (e.g. review by van der Klis 2006).

Also, BH and NS systems can be separated in the radio/X-ray luminosity plane (while in the hard state), with BH systems being radio brighter (Migliari & Fender 2006; Gallo, Degenaar & van den Eijnden 2018). Similarly, the hard Comptonized component tends to have a higher temperature in BH systems (Burke, Gilfanov & Sunyaev 2017). However, the loci of BHs and NSs overlap in these properties, so they cannot be used to determine the accretor definitively in an individual source, particularly where a source shows unusual properties.

Other properties of an accreting system can give a definitive determination of whether the accreting object is a BH or an NS. To confirm a BH accretor requires a dynamical mass measurement, which is greater than possible NS masses (e.g. Bolton 1972; Webster & Murdin 1972; Orosz & Bailyn 1997), since there are no particular accretion properties, which are unique to BHs. Conversely, there are several properties, which are confirmed as unique to NSs, since the NS surface can provide an additional location for emission components and they can support large-scale magnetic fields. The emission from this surface may be detected directly as a soft (0.1–0.3 keV) blackbody-like component (e.g. Brown, Bildsten & Rutledge 1998). This component is much fainter than the accretion luminosity, so cannot be identified during the first outburst in which a source is detected and requires sensitive observations to detect. Also, NSs can pulse coherently on their spin period, which can be observed at wavelengths from radio (Hewish et al. 1968) to X-ray (e.g. review by Patruno & Watts 2012). A further feature of XRBs...
1.1 Swift J1858.6–0814

The low-mass X-ray binary Swift J1858.6–0814 has been in its first observed outburst since late 2018 (Krimm et al. 2018). The X-ray emission in the initial phase of the outburst was highly variable as was the emission in other wavebands (Fogantini et al., in preparation; Ludlam et al. 2018; van den Eijnden et al. 2020; the NICER 0.5–10 keV count rate peaks at over 650 count s$^{-1}$ within 200 s of intervals at $\approx 2.5\text{ count s}^{-1}$ (Fogantini et al., in preparation), much larger than the typical tens of per cent RMS on these time-scales (McClintock & Remillard 2006). We refer to this stage of the outburst (all observations in 2018 and 2019) as the flaring state. The X-ray spectra were also extremely hard: $\Gamma < 1$ if fitted with a simple power law, (Kennea & Krimm 2018; Ludlam et al. 2018), compared to typical $\Gamma > 1.5$ (e.g. Zdziarski, Lubinski & Smith 1999).

This may be explained by the contribution of reflection and absorption: they also show a strong neutral iron K$\alpha$ line and K edge (Reynolds et al. 2018; Hare et al. 2020) and soft X-ray emission lines (Buisson et al. 2020a). It also shows P-Cygni lines in its optical spectra, which look similar to those seen in several BH XRBs (Castro-Segura, in preparation; Munoz-Darias et al. 2019; Muñoz-Darias et al. 2020), as well as strongly variable optical emission (Pace et al. 2018). These properties have led to Swift J1858.6–0814 being viewed (Hare et al. 2020) as an analogue of V404 Cyg (Gandhi et al. 2016; Motta et al. 2017; Walton et al. 2017) and V4641 Sgr (Wijnands & van der Klis 2000; Revnivtsev et al. 2002), which have been dynamically confirmed as hosting BHs (Casares, Charles & Naylor 1992; Orosz et al. 2001, respectively). Swift J1858.6–0814 also lies within the range occupied by BHs in the radio-X-ray plane (van den Eijnden et al. 2020). However, recent observations of Swift J1858.6–0814 have shown qualitatively different X-ray properties, suggesting a state change while the source was unobservable due to Sun constraint (between 2019 November and 2020 February), although the properties of the initial phase were not typical of a canonical state (e.g. van der Klis 1994). In the 2020 observations, the flux level is much steadier and the strong iron line and edge are absent (and fig. 1 of Buisson et al. 2020b). These observations have also shown Type I X-ray bursts in both NACER and NuSTAR data (Buisson et al. 2020c), unambiguously identifying the compact object as an NS.

In this paper, we analyse the Type IX-ray bursts detected in NACER and NuSTAR data of Swift J1858.6–0814.

2 OBSERVATIONS AND DATA REDUCTION

We have inspected the NACER (Gendreau et al. 2016) light curves from 2020 by eye. Apparent Type I bursts are present in OB-SIDs 3200400106, 3200400111, 3200400114, 3200400121, and 3200400122, corresponding to March 6, 11, 14, 21, and 22.

We begin with the calibrated, unfiltered events file from HEASARC (event.cl/nl32004001**.0mpu7.ufa.evt). We use the standard filters$^1$ to produce good time intervals apart from the undershoot range, which we relax from $\leq 200$ to $\leq 300$ s$^{-1}$ for the first Type I burst and $\leq 250$ s$^{-1}$ for the second. This is required due to high optical loading due to the relatively low Sun angle. Additionally, to include the peak of the second burst, we relax the offset from the nominal target direction slightly, using 0.015$^5$ rather than 0.015$^5$. This is a small change from the standard value, so data during this time are unlikely to show significant deviations from the standard calibration. Further, the fourth burst

\footnote{For further information on the filters, see heasarc.gsfc.nasa.gov/teams/ftools/headas/nimaketime.html.}
occurs during passage through the South Atlantic Anomaly (SAA) and the overshot rate reaches close to 5 s$^{-1}$, so is removed by standard filtering. We remove these filters in order to show the light curve but note that the spectrum may be affected.

We then use NICERCLEAN to produce a clean events list, which we then barycentre to the ICRS reference frame and JPL-DE200 ephemeris. From this, we extract spectra and light curves using XSELECT.

We use NuSTAR (Harrison et al. 2013) OBSID 90601308002, which overlaps with NICER OBSID 3200400106. We reduce this using the standard NUPipeline and NUProducts software, version 1.9.0. We use a source region of a circle of radius 2 arcmin centred on the centroid of the detected counts. We use a background region of a circle of radius 2 arcmin from a source-free area of the detector.

3 RESULTS AND DISCUSSION

3.1 Long-term light curve and burst recurrence time

We show the light curve of Swift J1858.6–0814 since leaving Sun constraint in 2020, showing times of observed Type I bursts (purple). In addition to the long-term flux decrease, several dips, and eclipses are visible; these will be considered in detail in future work. The full NICER light curve is shown in black at a resolution of 40 s and the bursts (purple) extend to their maximum count rate at 0.1 s resolution. The zero-point for the time axis is the start of 2020 February 25 (MJD 58904).

The count rate shows a secular decrease throughout the whole of this period, punctuated by short dips and eclipses as well as the five Type I bursts analysed here. The drop in persistent count rate from the first to the last burst was by a factor of around 4 and bursts were, in general, brighter at the start of 2020 February 25 (MJD 58904).

The offset between the NICER flux and the nominal NICER pointing is around 15 arcsec, which is less than the 1 arcmin nominal pointing stability of NICER (Arzoumanian et al. 2014). This shows that the X-ray bursts are from Swift J1858.6–0814.

3.2 Confirmation of source of Type I bursts

The first burst was observed by both NuSTAR and NICER. We show a NuSTAR image of the sky around Swift J1858.6–0814 in Fig. 2. This shows that, to the resolution available to NuSTAR, only one source is apparent in the NICER field of view and the location of the Type I burst flux is consistent with the location of the persistent emission. The offset between the NuSTAR position and the nominal NICER pointing is around 15 arcsec, which is less than the 1 arcmin nominal pointing stability of NICER (Arzoumanian et al. 2014). This shows that the X-ray bursts are from Swift J1858.6–0814.

3.3 Type I X-ray burst light curves

The light curves for each Type I burst are shown in Fig. 3. Each burst has a fast rise, lasting \( \leq 3 \text{s} \), a single peak and fades to being undetectable over the persistent level within up to \( \approx 40 \text{s} \). The decay of each burst, except the first, has an initial fast drop (within \( \approx 2-3 \text{s} \) of the peak) followed by a slower exponential fade, lasting the remainder of the time (up to \( \approx 40 \text{s} \)) when the burst is observable over the persistent flux. This fast drop is by a greater factor in brighter bursts (Fig. 4); for example, this drop is by a factor of \( \approx 2.5 \) in burst 1 but \( \approx 4 \) in burst 4. This shape is typical of Type I bursts fuelled by helium (Galloway et al. 2008a). Helium fuelled bursts can arise either when the accreted fuel is hydrogen poor or when accreted hydrogen burns stably between bursts; the binary orbital period is too long (\( \approx 76840 \text{s} \), Buisson et al. 2020c) for a helium white dwarf companion and hydrogen is present in the optical spectra of the accretion disc/wind (Muñoz-Darias et al. 2020) so the latter case is more likely. The upper limits on the burst recurrence time (1.4 d in the best case) are long enough that sufficient hydrogen burning is plausible. The first burst is considerably fainter (peaking at \( \approx 290 \text{count s}^{-1} \) over 0.5–10 keV; the next faintest, burst 4, peaks at \( \approx 600 \text{count s}^{-1} \) and shorter than the others. Apart from the fourth, each burst is stronger than the previous one, while the persistent count rate decreases; this could be due to partial burning of the accreted material occurring outside bursts producing more H-poor fuel in the latter bursts, if more inter-burst burning occurred due to a longer recurrence time.
Figure 2. 3–50 keV *NuSTAR* image of the sky around Swift J1858.6–0814. Left-hand panel: over the full (26.7 ks on source time) observation; only a single point source is apparent, at the position of Swift J1858.6–0814. Right-hand panel: during the Type I burst only; the source position matches the position during the full observation. The Nicer field of view is shown by the black circle and the nominal pointing direction by the black cross.

Figure 3. Light curves of each Type I burst, in order of occurrence. Purple: 0.7–10 keV *NICER*; red: 3–10 keV *NuSTAR*, scaled (increased by a factor of 5) and offset (by +600 count s$^{-1}$). Each burst has had the persistent rate (the mean rate from 50–200 s before the burst) subtracted. The shaded regions are the 1σ Poisson uncertainties.

Figure 4. Light curves of each Type I burst, in order of occurrence from the bottom to top. Purple: 0.7–10 keV *NICER*. Each burst is offset from the previous by a factor of $10^{0.5}$. Each burst has had the persistent rate (the mean rate from 50–200 s before the burst) subtracted. The cooling tail is similar for each burst but bursts 2, 3, and 5 have a stronger initial peak. The shaded regions are the 1σ Poisson uncertainties.

3.4 Time-resolved spectroscopy

We extract time-resolved spectra for each Type I burst using time intervals containing a minimum number of photons. First, we estimate the persistent emission from the interval from 200 to 50 s before the burst peak. We then define the start of the burst: we take a light curve binned to 0.1 s and find the final bin before the burst which is not above the persistent rate. We define the burst as starting at the end of this bin. Starting from this point, we extract spectra from time intervals containing at least 300 counts in excess of that expected from the persistent rate. We then fit the spectrum of the burst emission as the difference between each burst spectrum and the persistent spectrum (this is performed by treating the persistent emission as the background). We initially model the burst emission with a single blackbody. Apart from around the burst peaks, the spectra are described well by this model. However, spectra around the peaks of the second, third, and fifth bursts are broader than a simple blackbody and in the fits show excess emission at low energies. We test two alternative phenomenological models to explain this excess: allowing the normalization of the persistent emission to change by a factor $(1 + f_o)$ (Worpel, Galloway & Price 2013) or adding a second blackbody. The former case requires a model for the
bursts observed during the soft state.

of the bursts (mentioned throughout this work) which match other
χ single blackbody gives a poor fit (total fit statistics for burst 5 for the spectra from times where a
first blackbody component’s radius around the burst peak. The
and provide similar peak fluxes and qualitative behaviour of the

226.0/212 = 1.066,

\( \chi^2/\text{dof} = 73.5/83 \) when
\( \chi^2/\text{dof} = 78.7/76 \) for the double blackbody model; and
\( \chi^2/\text{dof} = 73.5/83 \) when varying the persistent emission. This implies a weak preference for
a change in the strength of the persistent component but both models
are statistically acceptable so we regard both options as possible.

A single blackbody (navy) is a poor fit; two blackbodies (yellow) or a contribution
proportional to the persistent flux (green) both give similarly good fits.

Both of these burst models provide good fits to all spectra (Fig. 5)
and provide similar peak fluxes and qualitative behaviour of the
first blackbody component’s radius around the burst peak. The
total fit statistics for burst 5 for the spectra from times where a
single blackbody gives a poor fit (\( \chi^2/\text{dof} = 78.7/76 \)
for the double blackbody model; and \( \chi^2/\text{dof} = 73.5/83 \)
when varying the persistent emission. This implies a weak preference for
a change in the strength of the persistent component but both models
are statistically acceptable so we regard both options as possible.

Parameters of the fits of each of these models to burst 5 are shown
in Fig. 6. Bursts 2 and 3 show similar features with the lower signal;
burst 1 has much lower signal; and we do not analyse burst 4 in detail
due to the enhanced background from the SAA.

The area of the blackbody increases around the Type I burst peak
before reducing and settling to a steady value for the majority of
the burst tail, characteristic of PRE. Both well-fitting models (two
blackbodies or additional persistent emission) show a similar degree
of expansion, by around a factor of 2 over the radius in the tail of
the burst, once the radius has settled to a steady value. The dip
in blackbody radius after the burst peak to below the tail value is
typical of bursts while accreting in the soft state, which agrees with
our identification from the persistent spectrum, and is likely due to
a changing colour-correction factor (Güver, Psaltis & Özel 2012a;
Güver, Özel & Psaltis 2012b; Kajava et al. 2014).

These fits show a fast rise and smooth decay in bolometric flux. The
apparent double peak in the flux curve for the single blackbody model
is likely due to the poor fit around this time, although double peaks in
bolometric luminosity have been seen in other PRE bursts (Jaisawal
et al. 2019). The comparatively smooth flux profile contrasts with the
fast drop in count rate after the peak; the difference being due to the
higher temperatures early in the decay producing a lower count rate
for a given flux (when convolved with the instrument response, given
the NICER effective area curve and the temperatures concerned).

Near the times of the Type I burst peaks (within about 2 s), there
is an excess of soft emission over the simple blackbody model. Similar
excesses have been seen in Type I bursts in many other
sources observed with NICER, e.g. Aql X-1 (Keek et al. 2018a),
4U 1820–30 (Keek et al. 2018b), and SAX J1808.4–3658 (Bult
et al. 2019). This could be due to other extra components such as
reemission from the disc (corresponding to the extra blackbody, Keek
et al. 2018a) or enhanced accretion through Poynting–Robertson drag
(corresponding to the change in persistent emission normalization,
Worpel et al. 2013). There may also be a deviation from a simple
blackbody due to Comptonization (Keek et al. 2018b) or scattering
processes in the atmosphere (Romani 1987). The data for the X-ray
bursts presented here are not sensitive enough to distinguish between
these possibilities clearly.

3.5 Distance estimate and implications

Since the later Type I bursts (certainly burst 5, with some evidence
also in bursts 2 and 3) show PRE, their peak luminosity should be
governed by the Eddington limit. The observed flux can then be used
to estimate a distance. Initially, we use \( L_{\text{Edd}} = 3.79 \times 10^{38} \text{ erg s}^{-1} \),
found empirically by Kuulkers et al. (2003) to be suitable for NSs at
known distance, and to have an accuracy of 15 per cent for source-
to-source variation. This matches the Eddington limit of a helium
atmosphere around a 1.4 M\( \odot \) object.

We take the peak flux from the second, third and fifth Type I
bursts (which are consistent with each other; different temperatures
mean that these correspond to different count rates). We use the
model of the burst including a scaled persistent emission component
(see Section 3.4), although the double blackbody model gives very
similar results. For each burst, we use the least-squares average of the
fluxes from intervals which are consistent within 1σ of the highest
value. These values are consistent with each other and their average
is \( 1.1 \pm 0.1 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1} \), which gives a distance of

\[ D = 16.7^{+1.8}_{-1.3} \text{ kpc (1σ)}. \]

This puts Swift J1858.6–0814 at the far side of the Galaxy; given its
Sky coordinates \( (l = 26.3894, b = -5.3237) \), this distance gives a
Galactic (cylindrical) radius of 10 kpc and a height of 1.5 kpc below
the Galactic plane.

Applying a prior for the relative density of the Galaxy along the
line of sight (using the Galaxy model of Dehnen & Binney 1998;
Grimm, Gilfanov & Sunyaev 2002; see also Gandhi et al. 2019)
reduces this distance slightly, due to the higher density of objects.

Figure 5. Comparison of different models for the net burst emission at the
peak of the burst (the spectrum with the highest count rate in Burst 5). A single
blackbody (navy) is a poor fit; two blackbodies (yellow) or a contribution
proportional to the persistent flux (green) both give similarly good fits.
closer to the Galactic centre, giving

\[ D = 16.2^{+1.5}_{-1.2} \text{ kpc (1}\sigma).\]

From the relative densities of the components of the Galactic model at this position, we infer that Swift J1858.6–0814 is most likely (75 per cent) to be a disc object but could also be part of the halo (25 per cent). A bulge origin is highly unlikely \[ P(\text{Bulge}) = 7 \times 10^{-6}.\]

There are systematic effects, which may affect this distance estimate (e.g. Galloway, Özsel & Psaltis 2008b). Many of these, such as differences in NS mass and photosphere metallicity, are implicitly included by the empirical nature of the critical luminosity (and its uncertainty) measured by Kuulkers et al. (2003). However, the effects of obscuration in high inclination sources are not accounted for – Kuulkers et al. (2003) find that in some high inclination sources the observed PRE luminosity is significantly lower. In this case, the photosphere may be partially obscured by larger components of the system, principally the disc. For the simple case of a razor-thin disc, the disc can obscure up to half of the NS so the flux may be underestimated by up to a factor of 2 and the distance may actually be smaller by a factor of up to \( \sqrt{2}.\) This factor is mitigated by reflection of the radiation intercepted by the disc but may be increased by a thick disc (He & Keek 2016).

To show the magnitude of these effects, we show distance estimates for various specific values of metallicity and inclination in Fig. 7 and Table 1. We calculate the distances by replacing the empirical peak luminosity from Kuulkers et al. (2003) with the theoretical Eddington luminosity (e.g. Lewin et al. 1993) modified by the anisotropy factor \( (\xi_b)\) from (He & Keek 2016),

\[ L_{\text{Obs}} = \frac{8\pi Gm_p M_{\text{NS}} c}{\xi_b \sigma_T (1 + X)(1 + z(R))}, \]

where \( G \) is the gravitational constant, \( m_p \) is the proton mass, \( M_{\text{NS}} \) is the NS mass, \( c \) is the speed of light, \( \sigma_T \) is the Thomson cross-section, \( X \) is the hydrogen mass fraction, and \( z(R) \) is the gravitational redshift at the photospheric radius \( R.\) We show the two extremes of likely metallicity, pure helium \( (X = 0)\) and a cosmic abundance of hydrogen \( (X = 0.739).\) Since it shows eclipses (Buisson et al. 2020c), Swift J1858.6–0814 is at high inclination; from He & Keek (2016), the appropriate reduction in apparent luminosity \( (\xi_b^{-1})\) for inclinations of 70°–80° is a factor of 0.85–0.65. For each combination of parameters, we show the distance estimate for an NS...
and $2.3^{+0.2}_{-0.15} \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$, in chronological order. If the persistent emission has the same anisotropy as the burst, this implies an Eddington fraction $\dot{m}_{\text{Edd}} = 0.20^{+0.01}_{-0.02}$, $0.16^{+0.01}_{-0.02}$, $0.14^{+0.01}_{-0.02}$, $0.09^{+0.01}_{-0.02}$, and $0.036 \pm 0.004$ for material in the accretion flow (calculating $L_{\text{Edd}}$ for $X = 0.73$). However, the disc and boundary layer may have more anisotropic emission than the burst from the NS surface (e.g. He & Keek 2016), so the true Eddington fraction could be somewhat higher. The exact factor depends on the details of the accretion structure and the inclination; for a flat disc (which provides all the persistent flux) observed at $70^\circ$–$80^\circ$, the increase is by a factor of 1.2–2. This is similar to the range at which helium fuelled bursts are expected and observed (Galloway et al. 2008a) but extends slightly higher, so there could be some influence of residual hydrogen in the burning material.

Our distance estimates are all relatively large (Galloway et al. 2008a; Gandhi et al. 2019) but not unprecedented (e.g. Homan et al. 2014) for an XRB. The absorbing column density ($\approx 2 \times 10^{21}$ cm$^{-2}$) is comparatively low for such a distant source, but the total Galactic column density in the direction of Swift J1858.6–0814 is similar ($1.8 \times 10^{21}$ cm$^{-2}$; HI4PI Collaboration et al. 2016). A large distance can also help in explaining the strong variability observed in the initial state of Swift J1858.6–0814 (during 2018–9): it is comparatively faint for a binary but strong winds (Muñoz-Darias et al. 2020) and variability (Ludlam et al. 2018) are often explained by a high Eddington rate (King & Pounds 2003; Grupe 2004). During the flaring state but between flares, the observed flux of Swift J1858.6–0814 was $\approx 2.5 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ (Hare et al. 2020), which is an order of magnitude lower than the Eddington luminosity (and correcting for any anisotropy is likely only to increase the strength of this). If much of the variability was due to obscuration, the intrinsic luminosity would also have been above Eddington at other times.

### 3.6 Pre-burst oscillations

We also looked for mHz QPOs, which are sometimes found before an X-ray burst (e.g. Revnivtsev et al. 2001; Altamirano et al. 2008; Mancuso et al. 2019). We used $0.5$–$10$ keV light curves at 1-s resolution and applied the Lomb–Scargle periodogram (Lomb 1976; Scargle 1982) to each gapless light curve, excluding periods of dipping and eclipses. In the five cases, where we detected the type-I X-ray bursts, we searched for the oscillations before and after the X-ray bursts. To estimate the significance level, we followed the approach of Press et al. (1992), which assumes white noise and takes as a number of trials the number of frequencies explored.

We detected an mHz QPO at a significance of $5.8\sigma$ in the 1.8 ks of data before the 5th X-ray burst (Fig. 8). The mHz QPO has an average frequency of $9.6 \pm 0.5$ mHz and a fractional rms amplitude of $2.2 \pm 0.2$ per cent (0.5–10 keV). There is no evidence of oscillations in the $\approx 600$ s of data after the X-ray burst, with a 90 per cent upper limit on the rms amplitude of 1.2 per cent ruling out that the same strength of oscillation continues. We also found marginal evidence of QPOs in at least three other cases; however, the data sets are relatively short ($\lesssim 500$–$700$ s), and therefore it is not possible to understand if they are real or the product of red noise. The upper limits to the QPO amplitude for the time segments prior

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To reduce the range of these estimates, we can consider whether particular values of parameters generating the systematic uncertainty are preferred over other evidence. The eclipse duration implies an inclination of at least $70^\circ$ (Buisson et al., in preparation; Buisson & Buisson are preferred by other evidence. The eclipse duration implies a distance of Galactic sources along this line of sight.

The atmospheric composition of a Type I bursts in Swift J1858.6–0814 was $\approx 2.5 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ (Hare et al. 2020), which is an order of magnitude lower than the Eddington luminosity (and correcting for any anisotropy is likely only to increase the strength of this). If much of the variability was due to obscuration, the intrinsic luminosity would also have been above Eddington at other times.

### Table 1. Distance estimates (kpc) for various gas compositions and inclinations

| Component | $i = 70^\circ$ | $i = 80^\circ$ |
|-----------|---------------|---------------|
| Pure helium | $16.6^{+0.9}_{-0.8}$ | $14.6^{+1.8}_{-1.7}$ |
| Cosmic abundances | $12.1^{+0.6}_{-0.6}$ | $11.1^{+0.5}_{-0.5}$ |

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2This was measured for the $3$–$78$ keV band, which for the spectral shape of this observation includes the majority of flux; any bolometric correction will only increase the strength of super-Eddington behaviour.
the burst emission. This would be expected for disc, NS surface or coronal emission so long as this is not strongly equatorially beamed.

The characteristics of the mHz QPOs we found here are consistent with those found in 6 other NS systems (but compare Linares et al. 2012, Revnivtsev et al. 2001; Altamirano et al. 2008; Strohmayer & Smith 2011; Lyu, Ménendez & Altamirano 2014; Lyu et al. 2015; Strohmayer et al. 2018; Mancuso et al. 2019) and are usually explained as being the product of marginally stable burning of He on the NS surface (Heger et al. 2007). This is the seventh NS system that shows this type of QPOs. The fact that we do not detect more episodes of mHz QPOs could either be due to their intrinsic absence or to detection difficulty: the mHz QPOs are not always present in the X-ray light curves (they are state-dependent and even in a given state, there is not yet a clear physical trigger for them, see Altamirano et al. 2008; Mancuso et al. 2019, etc.); in addition, the frequency and amplitude of these QPOs are very low, and therefore to acquire enough QPO cycles and sufficient signal-to-noise ratio, uninterrupted data sets longer than 1000–1500 s are generally needed to unambiguously detect them.

3.7 Burst oscillation search

We searched each of the X-ray bursts observed with NICER for the presence of burst oscillations, but did not detect any significant signals. To search for oscillations, we constructed a 1/8192 s time-resolution light curve for each X-ray burst, using only those events in the 1–8 keV energy band. These light curves all started 10 s prior to the burst onset, and had durations of 40 s. For each considered X-ray burst, we applied a $T = 2, 4, 8$ s duration window selection, and searched the 100–2000 Hz frequency range for excess power over the expected noise distribution. No such excess was observed, to a 95 per cent confidence upper limit of approximately 15 per cent fractional amplitude in the most sensitive segment (the peak light curve of burst 5). We note, however, that the vast majority of considered segments had much lower averaged count rates, and thus substantially higher upperlimits. With typical upper limits ranging between 30 and 80 per cent fractional amplitude, our results are therefore not especially constraining.

4 FURTHER DISCUSSION

4.1 Implications of the NS accretor

The identification of the accretor in Swift J1858.6–0814 as an NS informs several outstanding questions relating to the properties of Swift J1858.6–0814. It fits with the low coronal temperature found in Hare et al. (2020), since NSs tend to have lower coronal temperatures than BHs (Burke et al. 2017). However, the NS accretor implies an unusual location in the radio-X-ray plane: Swift J1858.6–0814 appears relatively X-ray faint for a NS XRB (van den Eijnden et al. 2020). This could imply that Swift J1858.6–0814 has an intrinsically unusually low X-ray/radio luminosity ratio or that the observed X-ray luminosity is unrepresentatively low. The latter case would support a model in which the X-ray emission (which may already be comparatively low due to anisotropy, e.g. He & Keek 2016) is usually obscured by the high inclination disc, apart from during the flares, which represent the true intrinsic luminosity, when viewing the central source directly through a gap in the (irregular) disc surface.
Swift J1858.6–0814 has previously been compared with the BH XRBs V4641 Sgr and V404 Cyg (e.g. Hare et al. 2020). All of these sources have shown strong variability due to some combination of changes in intrinsic flux and obscuration, although the relative contribution of these two effects is not yet clear (e.g. compare Walton et al. 2017; Koljonen & Tomsick 2020). The relative radio loudness also provides a further similarity with V404 Cyg, which is unusually radio-loud for its inclination (Motta, Casella & Fender 2018). The identification of Swift J1858.6–0814 as an NS XRB means the flaring behaviour in these sources must now be explained in a model which is compatible with an NS accretor. In particular, extreme variability from processes very close to the event horizon may be ruled out, since an NS is significantly larger than its Schwarzschild radius.

4.2 Bursts in the flaring state?

Swift J1858.6–0814 had been active for over a year before any Type I bursts were detected; there are several means to explain the non-detection of bursts during this period. First, there may truly have been no bursts, due to the different accretion regime during this period. In a model, where variable obscuration causes much of the strong variability, the intrinsic accretion rate was much higher during the flaring period, so would likely have induced stable nuclear burning of both hydrogen and helium. Additionally, in this model, the obscuration between flares would have impeded observation of any Type I bursts which occurred while the NS was obscured (which is the majority of the duty cycle). It is also possible that bursts were observed but not identified if they occurred at the same time as flares. The observed flares are all different in spectrum, light curve and/or duration to thermonuclear bursts; however, the variety of flares means that it is possible that a burst coincident with a flare would go unnoticed. Finally, it is also possible that bursts did occur during this phase of the outburst but, by chance, not during NICER observations of Swift J1858.6–0814. Overall, it is unsurprising that X-ray bursts had not been detected in the flaring state, whether or not they occurred.

4.3 Comparison with other similar sources

We can also compare the flaring state to other strong variability regimes in NSs. Two famous NS systems exhibiting flare-like behaviour are the Rapid Burster (MXB 1730–335, e.g. Hoffman et al. 1978) and Bursting Pulsar (GRO J1744–28, Fishman et al. 1995). The Rapid Burster shows many (up to thousands per day) ‘rapid’ bursts in addition to Type I bursts; these rapid bursts are much shorter (<10 s) and more regular in cadence than the flares of Swift J1858.6–0814, so are probably different phenomena. The Bursting Pulsar is the archetypal example of Type II X-ray bursts (Kouveliotou et al. 1996). These bursts also differ markedly from the flares observed in Swift J1858.6–0814: The Type II bursts are again much shorter and are accompanied by a drop in emission following the burst. Therefore, the flaring state of Swift J1858.6–0814 is not explained as an example of these other unusual NS XRB states.

The high inclination NS LMXB EXO 0748–676 has also shown flaring episodes (Homan, Wijnands & van den Berg 2003), although these are more sporadically interspersed with other light-curve shapes and less prominent at harder energies than those in Swift J1858.6–0814.

Transitional millisecond pulsars (tMSPs) also have a ‘flaring’ accretion mode (de Martino et al. 2013; Bogdanov & Halpern 2015), although this occurs at much lower luminosity (=10^{34} erg s^{-1}) than the flaring state in Swift J1858.6–0814 (≥10^{36} erg s^{-1} observed).

The tMSP flaring mode can also show strong, variable absorption (e.g. Li et al. 2020), so could be an analogue with lower accretion efficiency.

There have not yet been measurements of the magnetic field strength in Swift J1858.6–0814; the closer comparison of the flaring state of Swift J1858.6–0814 with BH than NS systems could be because the magnetic field of its NS is low enough to be unimportant in its accretion flow, implying a relatively low magnetic field strength.

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DATA AVAILABILITY

The data underlying this paper are available in HEASARC.

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Table A1. Summary of burst properties.

| Burst number | Recurrence time (d) | Peak rate (0.7–10 keV counts s$^{-1}$) | Persistent flux (× 10$^{-10}$ erg cm$^{-2}$ s$^{-1}$) | Persistent accretion rate ($\dot{M}_{\text{Edd}}$) (mHz) | QPO frequency (mHz) | QPO amplitude ($\leq$0.6%) |
|--------------|---------------------|----------------------------------------|-----------------------------------------------|----------------------------------------|---------------------|-----------------------------|
| 1            | $\leq$0.4           | 590 ± 75                               | $\leq$4.5                                      | $\leq$1.0                               | $\leq$6.3            | $\leq$0.6%                  |
| 2            | $\leq$0.6           | 960 ± 100                              | $\leq$3.6                                      | $\leq$0.5                               | $\leq$9.3            | $\leq$0.6%                  |
| 3            | $\leq$0.6           | 1190 ± 110                             | $\leq$6.3                                      | $\leq$0.5                               | $\leq$9.3            | $\leq$0.6%                  |
| 4            | $\leq$0.6           | 740 ± 90                               | $\leq$6.3                                      | $\leq$0.5                               | $\leq$9.3            | $\leq$0.6%                  |
| 5            | $\leq$1.4           | 1600 ± 120                             | 1.900 ± 120                                    | 0.600 ± 0.64                            | 9.6 ± 0.5            | 9.6 ± 0.5                   |

Notes. Recurrence times are upper limits as bursts may have occurred between observations. Peak rate is the highest value in the 0.7–10 keV light curve binned to 0.1 s. Persistent flux is measured bolometrically. Persistent accretion rate is not corrected for the effects of anisotropy, which likely increase it by a factor of 1.2–2. The mHz QPO is measured over 0.5–10 keV.

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