Radiation Driven Warping of Accretion Discs Due to X-ray Bursts

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ABSTRACT

The outpouring of radiation during an X-ray burst can affect the properties of accretion discs around neutron stars: the corona can cool and collapse, the inner regions can be bled away due to enhanced accretion, and the additional heating will lead to changes in the disc height. In this paper, we investigate whether radiation from bursts can cause the disc to distort through a warping instability. Working in the limit of isotropic viscosity and linear growth, we find that bursts are more likely to drive disc warps when they have larger luminosities and longer durations. Therefore, warps will be most probable during intermediate duration bursts (IMDBs) and superbursts with evidence for photospheric radius expansion. Further, the development of warps depends on the disc viscosity with larger values of $\alpha$ increasing the likelihood of warp growth. We perform time-dependent evolution calculations of the development of warps during Type I bursts and IMDBs. Depending on the initial warp prior to the burst, we find the burst produces warps at $r \lesssim 50 r_g$ that rapidly grow and decay on second-long timescales, or ones that grow more slowly and cover a large fraction of the disc. The pulsations of warp at small radii appear to have the properties needed to explain the achromatic fluctuations that have been observed during the tails of some IMDBs. The large scale, slowly growing warps could account for the large reflection strengths and absorbing column densities inferred late in the 4U 1820-30 and 4U 1636-53 superbursts.

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

1 INTRODUCTION

X-ray bursts are produced by unstable nuclear burning of gas accreted onto the surfaces of weakly magnetic neutron stars (e.g., Lewin et al. 1993; Galloway & Keek 2021). The heat produced by the nuclear reactions is thermalized and radiated as X-rays by the stellar atmosphere (e.g., Suleimanov et al. 2011, 2012). Depending on the nature of the burning layer and the properties of the heat transfer through the atmosphere, the timescale of the burst may be $\sim 10$ s (known as a Type I burst), $\sim 100$ s (an intermediate duration burst; IMDB), or, on rare occasions, $\sim 1000$ s (a superburst) (e.g., Strohmayer & Bildsten 2006). Many thousands of bursts have been detected from over 100 galactic neutron stars (NSs), with the vast majority being the shorter Type I bursts (Galloway et al. 2008, 2020).

The lightcurve of most bursts follows the rapid rise and slower decay seen from explosive transients, although bursts may also exhibit features such as plateaus or multiple peaks in their lightcurves (e.g., in’t Zand et al. 2011; Barrière et al. 2015; Bult et al. 2019; Jaisawal et al. 2019; Güver et al. 2021; Pike et al. 2021; Güver et al. 2022). The peak luminosity often approaches, or even exceeds, the Eddington luminosity of the neutron star ($\approx 2.5 \times 10^{38}(M/M_\odot)$ erg s$^{-1}$, where $M$ is the mass of the NS). Therefore, bursts are a powerful source of X-ray photons that are explosively released into the stellar environment. Indeed, observational evidence indicates that bursts can couple to the surrounding accretion flow, significantly impacting both the disc and corona (e.g., Ballantyne & Everett 2005; Degenaar et al. 2018). For example, analysis of X-ray reflection features from the disc during two long superbursts showed evidence for structural changes in the disc on the timescale of the burst (Ballantyne & Strohmayer 2004; Keek et al. 2014b). The ‘persistent’ accretion-powered X-ray emission is frequently observed to be enhanced during bursts (e.g., Worpel et al. 2013, 2015; Güver et al. 2022; Zhao et al. 2022), which may result from an increase in the local accretion rate due to Poynting-Robertson drag on the inner disc from burst photons (Walker & Meszaros 1989; Walker 1992). In addition, hard X-ray deficits observed during bursts would naturally occur from cooling of the corona due to the burst of soft photons emanating from the NS (Maccarone & Coppi 2003; Ji et al. 2014; Sánchez-Fernández et al. 2020; Speicher et al. 2020; Chen et al. 2022). Recent numerical investigations of the interaction of bursts with accretion flows confirm that X-ray bursts will significantly affect the disc structure and environment in ways consistent with the observational signatures (Fragile et al. 2018; Fragile et al. 2020). These results suggest that X-ray bursts are an important probe of accretion disc physics around NSs.

While perhaps the most dramatic examples of burst-disc interactions occurs near the peak luminosity (e.g., the draining of the inner disc due to Poynting-Robertson drag; Fragile et al. 2020), there may be long-lived, or slowly growing, effects that only become significant during the fading tails of bursts. For example, rapid fluctuations in the light-curve have been seen during the decay of a small number of luminous bursts, particularly IMDBs (e.g., in’t Zand et al. 2005, 2011; Degenaar et al. 2013; Barrière et al. 2015). These fluctuations

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in brightness go above and below the regular decay of the burst and have a typical timescale of $\sim 1$ s. After a minute or two these fluctuations vanish as quickly as they appeared. Another example is found in the reflection analysis of the 4U 1636-53 and 4U 1820-30 super-bursts. In both cases, time-resolved modeling of the RXTE spectra found larger reflection fractions and obscuring column densities during the tail of the burst than at the peak of the burst (Ballantyne & Strohmayer 2004; Keek et al. 2014b). Taken together, these results suggest that X-ray bursts, especially the larger IMDBs and super-bursts, may cause structural changes to the disc that persist long after the peak luminosity.

Accretion discs illuminated by a strong central radiation source are subject to a warping instability (Maloney et al. 1996; Pringle 1996; Maloney et al. 1998; Ogilvie & Dubus 2001). Depending on the nature of the illumination and viscous properties of the disc, the non-linear growth of the warp can lead to strongly distorted discs that may precess on long time-scales (Pringle 1997; Wijers & Pringle 1999). This effect has been frequently invoked to explain long duration periodicities observed in some X-ray binaries (e.g., Sood et al. 2007), and, as a result, previous work on radiation driven warping of discs focused on the effects from steady, accretion-powered illumination (e.g., Ogilvie & Dubus 2001). However, it is interesting to consider whether a transient, but powerful, release of central radiation may also produce a temporary disc warp. If an unstable disc warp can be driven by an X-ray burst, then this may be a possible explanation for some of the interesting behavior seen in the tails of long duration bursts described above, and could comprise another probe of accretion physics using X-ray bursts.

This paper investigates two questions related to the warping of accretion discs by X-ray bursts. In Section 2 we evaluate the conditions necessary for a burst of a given luminosity and duration to warp the accretion disc, and estimate the radius of instability. In Section 3 we solve the evolution equation for a warped accretion disc to demonstrate the growth of the warping instability during bursts of different durations. A discussion of the results is presented in Sect. 4 while Sect. 5 contains our conclusions.

2 CRITERIA FOR THE DISC WARPING INSTABILITY DURING AN X-RAY BURST

2.1 The Critical Radius

Pringle (1997) compared the timescale for an accretion disc to warp due to illumination by luminosity $L_a$ to the one for a disc to locally flatten itself, and found that the warping instability occurs for disc radii $\gtrsim r_{\text{crit}}$ where

$$r_{\text{crit}} = \left( \frac{6\pi^2}{L_\ast} \eta \frac{M}{3\pi \nu^2 \Gamma_{\text{crit}}} \right)^{1/2}, \quad (1)$$

Here, $r_{\text{crit}} = R/r_g$ is the radius of the disc in units of gravitational radii ($r_g = GM/c^2$, where $M_\ast$ is the mass of the NS), $M$ is the accretion rate onto the NS, $\gamma_{\text{crit}}$ is a numerical factor determined by Pringle (1997) to be $\approx 0.32$, and $\eta = \nu_0/\nu_1$ (the ratio of the vertical and azimuthal shear viscosities). This equation is valid for radii far from the inner boundary, so that $\nu_1 \Sigma = M/3\pi$ where $\Sigma$ is the surface density of the disc.

In the case of an X-ray burst $L_a \approx L_b$, the burst luminosity, as we are most interested in the case where $L_b \gg L_{\text{acc}}$, the overall accretion luminosity of the system. However, it is convenient to scale $L_b$ by $L_{\text{acc}}$ in order to connect to the accretion rate of the disc. Thus,

$$r_{\text{crit}} = \left( \frac{6\pi^2}{L_{\text{acc}}(L_b/L_{\text{acc}})} \eta \frac{M}{3\pi \Gamma_{\text{crit}}} \right)^{1/2}, \quad (2)$$

but, since

$$L_{\text{acc}} = \frac{GM_\ast M}{R_*}, \quad (3)$$

where $R_*$ is the radius of the NS, we can eliminate $M$ and $L_{\text{acc}}$ from Eq. 2 leaving

$$r_{\text{crit}} = \left( \frac{6\pi^2}{L_b/L_{\text{acc}}} \eta \frac{R_*}{3\pi GM_\ast \Gamma_{\text{crit}}} \right)^{1/2}. \quad (4)$$

Finally, $M_*$ and $R_*$ can be replaced by the gravitational redshift factor at the surface of a NS (Lewin et al. 1993),

$$1 + z_* = \left( 1 - \frac{2GM_\ast}{R_* c^2} \right)^{-1/2}, \quad (5)$$

yielding our final expression for the critical radius for the warping instability due to an X-ray burst,

$$r_{\text{crit}} = \left( \frac{4\eta}{\Gamma_{\text{crit}} (1 - (1 + z_*)^{-2}) (L_b/L_{\text{acc}})} \right)^{1/2}. \quad (6)$$

Thus, given a prescription for $\eta$, the values of $r_{\text{crit}}$ can be mapped out in the $(z_*, L_b/L_{\text{acc}})$ plane.

2.2 The Minimum Burst Timescale

The critical radius criterion discussed above originates from comparing the timescale of the growth of a warp, $t_{\text{warp}}$, to the timescale for the disc to flatten itself locally (Pringle 1997). However, for an X-ray burst to drive a warp, the warping timescale must be faster than the burst duration, $t_{\text{burst}}$. That is, in addition to determining the radii at which the disc becomes unstable, we must require $t_{\text{warp}} < t_{\text{burst}}$ at those radii.

Following Pringle (1996, 1997) this inequality can be written as

$$t_{\text{burst}} > \frac{12\pi R \nu^2 \Omega}{L_{\text{acc}}(L_b/L_{\text{acc}})}, \quad (7)$$

where $\Omega$ is the angular velocity of the disc. For a thin, Keplerian disc far from the inner edge, we find

$$t_{\text{burst}} > \frac{12\pi M}{v_1} \frac{R^2 c_*}{3\pi H^2 \nu_{\text{acc}}(L_b/L_{\text{acc}})}, \quad (8)$$

where $c_\ast$ is the sound speed and $H$ is the disc scale height. Assuming $v_1 = \alpha c_\ast H$ (Shakura & Sunyaev 1973) and using Eq. 3 to eliminate $M$ and $L_{\text{acc}}$ yields

$$t_{\text{burst}} > \frac{4}{\alpha G M_*} \frac{R^2 c_*}{(L_b/L_{\text{acc}})H^2}. \quad (9)$$

The scale height of a gas-pressure dominated accretion disc with $e^-$ scattering opacity far from the inner boundary can be written as (e.g., Shakura & Sunyaev 1973)

$$H = (2.2 \times 10^3 \text{cm}) \alpha^{-1/10} \left( \frac{M_*}{M_{\odot}} \right)^{9/10} \left( \frac{M}{M_{\text{Edd}}} \right)^{1/5} r^{21/20}, \quad (10)$$

where $M_{\text{Edd}}$ is the Eddington accretion rate and we have assumed that the radiative efficiency of the disc is 0.1. As the dependencies

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1. This expression for $H$ is likely an underestimate during an X-ray burst, as the disc will inflate due to X-ray heating (Fragile et al. 2020).
on $\alpha$ and $M$ are relatively weak, the scale height can be approximated as

$$H \approx (2.2 \times 10^3 \text{ cm}) \left( \frac{M_*}{M_\odot} \right) r.$$  

(11)

Substituting this expression into Eq. 9, while also making use of Eq. 5 to eliminate the stellar radius, gives

$$t_{\text{burst}} \gtrsim (0.17 \text{ s}) \frac{(M_*/M_\odot)r}{\alpha(1 - (1 + z_*)^{-2})(L_b/L_{\text{acc}})}.$$  

(12)

Finally, evaluating the above expression at $r_{\text{crit}}$ using Eq. 6 gives the minimum burst duration needed to drive a disc warp at $r_{\text{crit}}$:

$$t_{\text{burst}} \gtrsim (2.8 \text{ s}) \frac{(M_*/M_\odot)\eta^2}{\alpha_r^2(1 - (1 + z_*)^{-2})(L_b/L_{\text{acc}})}.$$  

(13)

### 2.3 Results

We can now use Eqs. 6 and 13 to estimate the burst luminosities and durations needed to drive a warp at a particular radius on an accretion disc. However, before doing so, the ratio of the vertical and azimuthal shear viscosities, $\eta$, must first be defined.

Following the standard Shakura & Sunyaev (1973) assumption, the vertical shear viscosity is $\nu_v = 2\alpha c_s H$, and, as mentioned in Sect. 2.2, $v_c = \alpha c_s H$, where both $\alpha_0$ and $\alpha$ are treated as constants.

For isotropic viscosity and warps growing in the linear regime, $\alpha_2 = 1/2\alpha$ (Papaloizou & Pringle 1983; Nixon 2015), and therefore

$$\eta \approx \frac{1}{2\alpha}.$$  

(14)

This isotropic approximation for $\eta$ is used for the remainder of the paper. Since the timescale for the vertical viscosity to smooth out a disc warp is proportional to $v_c^{-1}$ (Pringle 1997), a larger $\alpha$ will increase this timescale and make it easier for radiation to drive a warp in an accretion disc.

Using this prescription for $\eta$, Figure 1 shows the estimated values of $r_{\text{crit}}$ and $t_{\text{burst}}$ as a function of $z_*$ and $L_b/L_{\text{acc}}$. Results are calculated for $\alpha = 0.05$ (left panel) and 0.1 (right panel). A stellar mass of 1.4 Ms is used for estimating $t_{\text{burst}}$ (e.g., Lattimer 2012). The panels show that both $r_{\text{crit}}$ (the colour map) and $t_{\text{burst}}$ (the contours) are strong functions of $L_b/L_{\text{acc}}$ and $\alpha$, but are not sensitive to $z_*$ once $z_* \gtrsim 0.2$. Recent measurements of the compactness of NSs indicate $z_* \approx 0.2$–0.3 (Miller et al. 2019, 2021), indicating that the burst luminosity and disc viscosity are the most important parameters for the growth of a disc warp.

In general, Fig. 1 shows that more luminous bursts lead to discs that are unstable to warping at smaller radii and thus require a shorter duration to grow the instability. To illustrate this, consider the evolution of a burst in this Figure. Once the burst ignites, the luminosity quickly evolves from $L_b \sim L_{\text{acc}}$ to its peak luminosity, moving horizontally from left to right in one of the panels of Fig. 1. While, in principle, the luminosity of the burst during this transition is sufficient to drive a warp instability at a large disc radius, the time the burst spends at these luminosities is too short for the instability to take hold. Only when the burst reaches its peak $L_b/L_{\text{acc}}$ and holds that luminosity for a sustained period of time will a disc warp be able to grow. The larger the peak luminosity, the less time is needed in order for an disc warp to develop, and this warp will grow at smaller radii. However, the growth of any disc warp will be arrested once the burst luminosity begins to fall. During the tail of the burst, the luminosity moves from right to left through the panel, and, depending on the speed of the decay, may evolve too quickly to drive any warps at large radii along the disc. Thus, we expect that bursts will be able to drive disc warps during the peak of the burst, with warps growing at smaller radii during more luminous bursts. The internal disc viscosity will work to smooth any warp during the tail of the burst.

As the contours show the minimum burst durations, bursts that can sustain a peak luminosity for 10s or 100s of seconds, such as a IMDB or a superburst, will have a strong impact on the disc. In this case, the long duration of the peak $L_b/L_{\text{acc}}$ means that a large fraction of the accretion disc could grow unstable to radiation driven warps, and lead to substantial growth of warps at smaller radii.

Figure 1 shows that the viscosity of the disc strongly impacts the critical luminosities needed to drive a warp. As expected from the isotropic viscosity assumption, a larger value of $\alpha$ will allow a warp to be driven at a lower luminosity. Many accreting NSs accrete at $\sim 0.01$ of their Eddington rate (Galloway et al. 2020), so $L_b/L_{\text{acc}} \sim 10^2$ is a reasonable estimate for the peak luminosity of an X-ray burst that does not exhibit photospheric radius expansion (e.g., Lewin et al. 1993). Therefore, if $\alpha = 0.05$ only superbursts are predicted to produce radiation driven disc warps at $r \sim 10^3 r_g$, as both IMDBs and Type I bursts are too short for a peak luminosity of $L_b/L_{\text{acc}} \sim 10^2$. However, if $\alpha = 0.1$, then Type I bursts with peak luminosities that last $\sim 5$ s and IMDBs will both be able to drive disc warps. Therefore, if observational evidence for disc warps can be obtained from Type I X-ray bursts, then this would indicate that $\alpha \gtrsim 0.1$ in those discs. Conversely, if the effects of disc warps are not found during superbursts, then $\alpha \lesssim 0.05$ in those systems.

### 3 EVOLUTION OF THE DISC WARPING INSTABILITY DURING AN X-RAY BURST

The results of the previous section showed that, depending on the strength of the disc viscosity, X-ray bursts may lead to a radiation driven warp instability in the surrounding accretion disc. In particular, X-ray bursts with durations longer than $\sim 10$ s, such as IMDBs and superbursts, could potentially cause a large fraction of the disc to become unstable to warping. To understand how this instability will impact the disc geometry, we must solve the evolution equation for a warped accretion disc subject to the radiative torque provided by an X-ray burst.

#### 3.1 Overview

To describe the evolution of a warp in an Keplerian accretion disc, we first define the local angular momentum density (Pringle 1992),

$$L(R,t) = (GM_*R)^{1/2} \ell,$$  

(15)

where $\ell$ is a unit vector normal to the annulus at radius $R$ at time $t$. To define $\ell$, consider an $x_\gamma z$ coordinate system located at each annulus, centered on the disc and with the $x$-axis pointing to the NS. With $\beta(R,t)$ as the local tilt angle of the disc and $\gamma(R,t)$ as the twist angle (i.e., the azimuth of the tilt), $\ell$ is

$$\ell(R,t) = (\cos \gamma \sin \beta, \sin \gamma \sin \beta, \cos \beta).$$  

(16)

Thus, $\ell$ measures the local warp of the disc, and the evolution of $L(R,t)$ describes the development of the warp. The strength of the

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2 See Ogilvie (1999) for a discussion on the treatment of non-linear effects on the viscosity and the implications for warped discs.
This assumption is valid for small warps ($\Psi < 1$) growing in the linear regime. To a good approximation, ($H/R$) can be considered constant for gas-pressure dominated accretion discs far from the inner edge (e.g., Svensson & Zdziarski 1994, their Eq. 8). Thus, we fix ($H/R$) = 0.0155 for all the calculations presented in this section which is sufficiently smaller than the two values of $\alpha$ considered ($\alpha = 0.05$ and 0.1).\(^3\)

For accretion discs around compact objects, it is useful to re-write Equation 18 in terms of $r = R/r_g$, $m = M_*/M_\odot$, and $\sigma = \Sigma/\Sigma_0$, where $\Sigma_0$ is a scaling factor for the surface density. We leave the units of time as seconds in order to more easily compare to X-ray burst lightcurves. The evolution equation can now be written as

$$\frac{\partial \mathcal{L}}{\partial \tau} = \frac{M_\odot}{r_g^2} \left\{ \frac{3\alpha(H/R)^2}{r} \frac{\partial}{\partial r} \left[ r^{1/2} (Gmr/\sigma)^{1/2} \frac{\partial}{\partial r} (|\mathcal{L}| r^{1/2}) \right] ight\}$$

$$+ \frac{1}{r} \frac{\partial}{\partial \tau} \left[ \left( \mu_1 r^2 \frac{\partial}{\partial r} \right)^2 - 3 \mu_2 \right] \mathcal{L}$$

$$+ \frac{1}{r} \frac{\partial}{\partial \tau} \left[ \frac{3}{2} \mu_2 \frac{\partial}{\partial r} \frac{\partial}{\partial r} + \mathcal{T} \right],$$  \(\text{(20)}\)

where $\mu_{1,2} = v_{1,2}/(r_g M_\odot)^{1/2}$, $\mathcal{L} = (Gmr/\sigma)^{1/2} \sigma \ell$, and $\mathcal{T} = \mathcal{T}/M_\odot \Sigma_0$. Given an initial $\mathcal{L}$ and boundary conditions at low and high

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**Figure 1.** The colour in each panel indicates the critical radius $r_{\text{crit}}$ at which an accretion disc becomes unstable to a radiation driven warp due to an X-ray burst of luminosity $L_b/L_{\text{acc}}$ from a NS with redshift factor $z$ (see Sect. 2.1). The contours plot estimates of the minimum burst duration $\Delta t_{\text{burst}}$ needed to drive the instability at $r_{\text{crit}}$ (Sect. 2.2) assuming a NS mass of 1.4 $M_\odot$. Both $r_{\text{crit}}$ and $\Delta t_{\text{burst}}$ significantly depend on the assumed viscosity parameter $\alpha$ in the disc. Considering a typical burst luminosity of $L_b/L_{\text{acc}} \approx 100$ (e.g., Galloway et al. 2020), when $\alpha = 0.05$ (left panel) a burst duration of several hundred seconds (e.g., a superburst) would be necessary to drive a disc warp at $r \sim 10^3 r_g$. However, if $\alpha = 0.1$ (right panel) a Type I burst lasting $\approx 5$ s which reaches the same luminosity can drive a warp at $\sim 100 r_g$. Longer bursts, such as an IMDB, at this luminosity would lead to warps developing at progressively smaller radii. The results show that, depending on the strength of the disc viscosity, radiatively driven disc warps can be driven by X-ray bursts over a wide range of durations.
high $r$, Eq. 20 can be integrated explicitly in time. Once $\mathcal{L}(r)$ is known at each timestep, both $\sigma(r)$ and $\ell(r)$ can be determined and the properties of the warped disc can be described.

### 3.2 Numerical Method

Equation 20 is integrated on a linear radial grid with inner radius $r_{\text{in}} = 3 \, r_g$ and outer radius $r_{\text{out}} = 401 \, r_g$ (with $\Delta r = 2 \, r_g$). The timestep for all calculations is $\tau = 5 \times 10^{-4} \, \text{s}$, which is $\approx 1.5 \times$ smaller than the minimum viscous timescale in the disc and satisfies the Courant condition. Following Martin et al. (2019b), the initial surface density profile defined on the radial grid is

$$\sigma_i(r) = \left( \frac{r}{r_{\text{in}}} \right)^{-1/2} \left[ 1 - \left( \frac{r_{\text{in}}}{r} \right)^{1/2} \right] \left( 1 - e^{-r/r_{\text{out}}} \right),$$

(21)

which reaches a maximum at $11 \, r_g$. This profile drives the surface density to zero at the inner and outer radii, enforcing zero torque boundary conditions. We also ensure that $d\ell/dr = 0$ at both boundaries.

Pringle (1997) found that the growth and evolution of a radiative driven warp depends on the initial tilt and twist profiles of the disc. Here, we define the initial tilt and twist of the disc as (Pringle 1997; Martin et al. 2019b)

$$\beta_i(r) = (0.01 \, \text{rad}) \left[ \frac{1}{2} \tanh \left( \frac{r - r_{\text{warp}}}{r_{\text{width}}} \right) + \frac{1}{2} \right],$$

(22)

and

$$\gamma_i(r) = (-2 \, \text{rad}) \left[ \frac{1}{2} \tanh \left( \frac{r - r_{\text{warp}}}{r_{\text{width}}} \right) + \frac{1}{2} \right],$$

(23)

where $r_{\text{warp}} = 200$ and $r_{\text{width}} = 25$. These functions describe a disc which possesses a small warp around the midpoint of the disc (Figure 2). This warp could develop between X-ray bursts from the persistent emission emanating from the NS boundary layer and disc corona, a wind moving across the disc surface (Quillen 2001), or dynamical effects from the binary companion star (e.g., Martin et al. 2014; Fu et al. 2015). To illustrate the dependence on the initial warp, we will also consider models where the starting $\gamma(r)$ is reduced by a factor of two (dashed line in Fig. 2).

The radiation torque density on the disc at radius $r$ due to a luminosity $L_\nu$ is (Pringle 1996; Ogilvie & Dubus 2001)

$$T = -\frac{L_\nu}{12 \pi r c} (\ell \times a),$$

(24)

where $a$ is a dimensionless integral that is proportional to $\partial \ell/\partial r$. We follow the procedure described in Appendix A of the paper by Ogilvie & Dubus (2001) to compute $T$ at each timestep including the effects of self-shadowing by regions of the disc inwards of $r$. The calculation of $T$ for use in Eq. 18 requires both $T$ and the normalization of the surface density profile, $\Sigma_0$, which is determined from the expression for $\Sigma$ from Eq. 19, and noting that $\Sigma \approx \Sigma_0 (r/r_{\text{in}})^{-1/2}$ far from the boundary (Eq. 21), we find

$$\Sigma_0 = \frac{c M}{3 \pi \alpha \left( \frac{H}{2} \right)^2 G M_* m_{\text{in}}^{1/2}}$$

(25)

This equation is evaluated using $\dot{M} = 2 \times 10^{-10} \, M_\odot \, \text{yr}^{-1}$, equivalent to approximately 1% of the Eddington rate (e.g., Galloway et al. 2020). The radiation torque is only applied for radii $9 \, r_g < r < 393 \, r_g$ to avoid regions where the surface density $\sigma$ is falling rapidly and to remain consistent with the zero torque boundary conditions.

To both ensure the zero-torque boundary condition and to mimic the effect of a steady accretion rate, $\mathcal{L}$ is set to its initial value for radii $r > 393 \, r_g$ at the end of every timestep. Thus, the outer boundary maintains the small twist and tilt defined by Eqs. 22 and 23. At the inner boundary, the disc would normally terminate at a boundary layer on the surface of the NS. However, modeling the boundary layer and its effect on the disc is beyond the scope of the current paper, so we follow a similar procedure and set $\mathcal{L}$ to its initial value for $r < 9 \, r_g$. As a result, any disc warp is removed at very small radii, as might be expected when interacting with a boundary layer. Appendix A illustrates the results when this condition is relaxed and disc warps are allowed to reach the inner boundary.

The evolution equation (Eq. 20) is integrated over time with $L_b$ following the lightcurve of either a 25 s long Type I burst or a IMDB that lasts 200 s. The lightcurves of both bursts are described by an exponential rise, followed by a plateau and a power-law decay (e.g., Barrière et al. 2015; Pike et al. 2021),

$$L_b = \begin{cases} 
L_0 \exp \left( -\frac{t_b}{\tau_g} \right) & 0 \leq t \leq t_{\text{peak}}, \\
L_{\text{plateau}} & t_{\text{peak}} < t \leq t_{\text{tail}}, \\
L_{\text{plateau}} \left( \frac{t_b}{t_{\text{tail}} - t_b} \right)^{\Gamma} & t > t_{\text{tail}},
\end{cases}$$

(26)

where $t_b$ is the burst start time, $\tau_g$ and $\tau_0$ are the characteristic rise and decay times, $t_{\text{peak}} = \sqrt{\frac{\tau_g}{\tau_0}}$ is the time to reach peak luminosity, and $t_{\text{tail}} = t_{\text{peak}} + t_{\text{plateau}}$ is the start time of the power-law decay, following a plateau of duration $t_{\text{plateau}}$. The plateau luminosity is
The initial disc warp is described by $\beta_i$ and $\gamma_i$ (Fig. 2), and the initial surface density is defined by Eq. 21. According to Sect. 2.3, a Type I burst with a peak luminosity of $L_0/L_{acc} \approx 100$ is not expected to drive a disc warp when $\alpha = 0.05$, and the left-hand side of Figure 4 confirms this prediction. Close inspection of the $\Psi$ panel for the $\alpha = 0.05$ calculation shows that the initial warp centered at 200 $r_g$ dissipates and propagates to higher and lower radii during the first 5 seconds of the burst, with no significant warp growth occurring during any part of the burst. Similarly, the disc surface density panel only shows a steady reduction of $\sigma$ in the inner disc due to the enhanced radial transport caused by the vertical viscosity $\nu_2$. The lack of any disc warping during the $\alpha = 0.05$ Type I burst calculation supports the validity of the analytical estimates of Sect. 2.3, and also indicates that our numerical method is not introducing spurious warps into the calculations.

Qualitatively different behavior is observed from the $\alpha = 0.1$ calculation (right-hand side of Fig. 4). In this scenario, substantial and repeated disc warps develop and dissipate at $r \lesssim 40 r_g$ starting at $\approx 3.5$ s and lasting through both the plateau and, in particular, the tail of the X-ray burst. The growth of disc warps in the $\alpha = 0.1$ Type I burst calculation is consistent with the predictions of Fig 1, although the expected critical radius is predicted to be $\sim 100 r_g$. The lower-right panel of Fig. 4 shows that these warp events are accompanied by increases in the disc surface density, resulting from the temporary build-up of material over the small range of radii in the warp.

Three significant disc warp events occur during the plateau phase of the burst, each getting progressively stronger; however, $\Psi < 1$ in all cases, indicating that the warps remain in the linear regime (Fig. 5; left panel). The growth and decay of the warps are due to the complex interactions between the disc viscosity attempting to flatten the disc, the radiation torque trying to warp the disc, and the effects of shadowing, which can significantly alter the pattern of radiation torque on the disc (see also Pringle 1997). This is illustrated in the right panel of Fig. 5 which plots $\Psi(r)$ at the time that $\Psi$ reaches its maximum (at 8.4 s). At this point, $\Psi$ peaks at 0.87 at $r = 17 r_g$. The warp is concentrated in the inner regions of the disc, where the flux and radiative torque is largest, but these radii also have the shortest viscous and diffusion timescales (see below), which will act to quickly reduce the warp. The disc just behind the warp (at slightly larger radii) is shadowed by the warped disc inside of it, which reduces the growth of the warp until the radiation torque can once again dominate.

The most striking aspect of the $\alpha = 0.1$ warping calculation are the repeated ‘pulses’ of warp during the tail of the burst that start at $\approx 12$ s and end at $\approx 21$ s. Each of these warps have $\Psi \lesssim 0.5$, and peak at $17 r_g$. To get a more physical view of the nature of these warps, the left panel of Figure 6 plots the time evolution of maximum disc tilt $\beta$ along the disc in degrees. The panel shows that the disc tilts remain small, as expected by the linear growth approximations made in our calculation. The right side of Fig. 6 shows part of the radial profile of $\beta(r)$ at the peak of one of the pulses during the tail of the burst and shows that it is concentrated at radii $\lesssim 25 r_g$. Therefore, while small, these warps may still subtend a non-negligible solid angle as seen from the neutron star.

The pulses of warp during the burst tail of the $\alpha = 0.1$ calculation occur at regular intervals of $\approx 0.3$ s. Figure 7 plots estimates of the three timescales important in warped discs\textsuperscript{4}. The solid and dashed

\textsuperscript{4} The dynamical time is $\sim 10^{-3}$ s at these radii and is off the scale of the plot.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{The radiative disc warp instability will be explored for two types of bursts, with lightcurves described by Eqs. 26 and 27. The first is a 25 s long Type I X-ray burst (left panel) which peaks at 2.8 s, followed by a 6 s long plateau and a power-law decay. The right panel shows the light curve for a 200 s IMDB that peaks at 10 s and has a 55 s long plateau before the power-law decay. In both cases, the peak luminosity of the burst is $2.6 \times 10^{38}$ erg s$^{-1}$, so that $L_0/L_{acc} \approx 100$.}
\end{figure}

The growth and evolution of the disc warp will depend on the value of the viscosity parameter $\alpha$ (Sect. 2). Therefore, in addition to the dependence on the initial disc warp, the effects of both the Type I burst and the IMDB on the disc are studied assuming either $\alpha = 0.05$ or 0.1. Our calculation procedure saves the local disc tilt, $\beta(r)$, the local disc twist, $\gamma(r)$, and the surface density, $\sigma(r)$, between $r_{in}$ and $r_{out}$ every 0.1 s. From $\beta(r)$ and $\gamma(r)$, we calculate the warp amplitude $\Psi(r)$ (Eq. 17) as a function of time, and use this quantity to measure the evolution and strength of any disc warp that develops. Interested readers are encouraged to view the movies found in the online Supplementary material to watch the full time evolution of $\Psi$, $\sigma$, and $\beta$.

\subsection{3.3 Results}

\subsubsection{3.3.1 Type I Bursts}

Figure 4 displays space-time plots of the disc warp amplitude $\Psi$ (Eq. 17; top row) and surface density $\sigma$ (bottom row) found from integrating the evolution equation (Eq. 20) during a Type I burst.
Disc Warps Driven by X-ray Bursts

Figure 4. The top row shows space-time plots of the disc warp amplitude \( \Psi \) (Eq. 17) during a Type I X-ray burst with \( \alpha = 0.05 \) (left) and 0.1 (right). Space-time plots of the disc surface density \( \sigma \) are shown in the bottom row. The burst does not cause a warp to grow in a disc with \( \alpha = 0.05 \), consistent with the expectations from Fig. 1. In this case, the surface density slowly decreases due to the enhanced radial transport from the vertical viscosity \( \nu \) (e.g., Pringle 1992). Rapid growth and decay of disc warps at \( r \lesssim 40 r_g \) is found when \( \alpha = 0.1 \), similar to the expectations of Fig. 1. The warping occurs during both the plateau and tail of the burst and are accompanied by an increase in the surface density within \( \approx 20 r_g \). The ‘pulses’ of warp during the tail of the burst are separated by \( \approx 0.3 \) s, in agreement with the vertical viscous timescale of the disc at these radii (Fig. 7).

The advection velocity is computed using the initial value of \( \Psi \) which is 0 over this range of radii (Fig. 2). Therefore, \( t_{\text{adv}} \) in Fig. 7 will be a lower limit. Given both the timescale (\( \approx 0.3 \) s) and radii (\( \approx 20 r_g \)) of the pulsations, we see that these properties are consistent with the vertical diffusion timescale in an \( \alpha = 0.1 \) disc. This is the primary timescale at which the disc attempts to flatten any warps. It appears that during the tail of the Type I burst, a mode in the disc is excited in which warp growth and destruction are locked on the same timescale. This lasts for several seconds before the decline in burst luminosity (and therefore radiative torque) reduces the ability of warps to grow at the required rate.

3.3.2 IMDBs

The results of the warp evolution calculations for the longer IMDBs are shown in Figure 8. As with the Type I burst models discussed above, the initial disc warp is defined with \( \beta_i \) and \( \gamma_i \) (Fig. 2). The left-hand side of the figure shows that no disc warp develops when \( \alpha = 0.05 \), similar to the Type I burst case. The results of Sect. 2 indicate that even longer bursts (such as superbursts), or luminosities several times larger, would be needed to drive a disc warp when \( \alpha = 0.05 \).

Turning to the \( \alpha = 0.1 \) calculation (right side of Fig. 8), we find repeated growth and decay of warps occurring at \( r \lesssim 50 r_g \) during the plateau of peak luminosity in the IMDB. The warps also lead to temporary increases in the surface density over the same range of radii. Additional details of the warps are shown in Figure 9, which plots the evolution of the peak \( \Psi \) during the IMDB. Unlike the pulsations...
seen in the Type I calculation, the warps found during the IMDB sometimes reach $\Psi > 1$, with the maximum value of 1.45 occurring at 38.1 s. These warps, therefore, enter the non-linear regime, moving outside the range of validity for this calculation. The right panel of Fig. 9 show that the peak of the warps are concentrated within $\sim 20 r_g$. The larger values of $\Psi$ naturally lead to increased disc tilts $\beta$, as shown in Figure 10. The largest disc tilt is 10.5 degrees and occurs 58.5 s into the IMDB.

Unlike the pulses seen in the Type I burst calculation, the repeated disc warps in the IMDB model occur almost exclusively during the plateau phase of the burst, with a single, final warp occurring 5.4 s into the tail, at $t = 70.4$ s. The pulses of warp in the IMDB calculation are separated by $\approx 3-4$ s, ten times longer than the ones found in the Type I burst. This timescale is consistent with the radial diffusion timescale at $r \lesssim 20 r_g$ (Fig. 7). Therefore, while the warps are quickly flattened by the vertical viscosity, the re-generation timescale is set by how quickly the disc can bring material through to the inner regions of the disc.

### 3.3.3 Reducing the Initial Warp

As demonstrated by Pringle (1997), the evolution of a disc warp is sensitive to the initial warp defined at $t = 0$. We investigate this here by repeating the $\alpha = 0.1$ calculations for both the Type I burst and IMDB with $\gamma/2$. The initial disc tilt remains $\beta$, but the change in the starting disc twist reduces the initial $\Psi$ of the disc (Fig. 2). The
resulting space-time plots of $\Psi$ and $\sigma$ are shown in Figure 11. The plots show a very different warp evolution than the previous calculations with $\gamma$ (Figs. 4 and 8). Rather than pulsations of disc warp that rapidly form and dissipate within $\sim 50 r_g$, we instead see a slowly growing disc warp that covers a large fraction of the disc. The warp grows during the plateau phase of each burst before declining in the tail. As a result, the warp reaches a higher value during the IMDB, but remains safely in the linear regime (the maximum $\Psi$ is 0.044).

Similarly, unlike the strong warp pulsations seen earlier, the $\gamma/2$ warps do not result in an increase in surface density. Interestingly, the radii of warp growth in these $\gamma/2$ calculations are closer to the values of the critical radii predicted by Fig. 1, indicating that the smaller initial $\Psi$ may be important in comparing to the analytical estimates of $r_{\text{crit}}$.

The evolution of the maximum disc tilt in the IMDB calculation with $\gamma/2$ is shown in the left-hand panel of Figure 12. The steady increase of $\beta_{\text{max}}$ during the plateau phase of the IMDB is clearly apparent, with $\beta$ reaching a maximum of 1.45 degrees at $t = 67$ s, shortly after the burst luminosity begins its decline. The disc tilt therefore grew $\sim 1.4$ degrees in $\sim 55$ s. Assuming the same rate of growth, a superburst with a plateau of $\sim 1000$ s (e.g., 4U 1636-53; Keek et al. 2014a,b) would generate a maximum disc tilt of $\sim 25$ degrees. The radial profile of the warp at $t = 67$ s is shown in the right panel of Fig. 12. The peak tilt occurs at $r = 49 r_g$ with a slow decline to larger radii. The profile is far less ‘peaky’ than the ones found with the $\gamma$ starting condition (e.g., Fig. 10), indicating that the complex feedback effects from shadowing are less important in the evolution of this warp.

To understand how a modest factor of 2 change in $\gamma$ can yield such a different outcome, Figure 13 plots the components of $\mathbf{T}$ for the $\gamma/2$ model. The figure show that the two torque densities at this location (which is close to the peak of the initial $\Psi$; Fig. 2) coincide for the first $\approx 1.5$ s of the calculation before diverging. The strongest torques are in the $x$ and $y$ directions and lead to procession of a tilted orbiting ring (e.g., Pringle 1996). The torques in these 2 directions show different behaviors depending on the initial disc twist, in particular in the $y$-direction where the torques have different signs. In the limit of no shadowing $\mathbf{T} \propto \hat{r} \times \partial \ell/\partial r$ (Ogilvie & Dubus 2001), which leads to terms proportional to $\partial \beta/\partial r$ and $\partial \gamma/\partial r$. Lowering the initial disc twist to $\gamma/2$ also reduces $\partial \gamma/\partial r$, which ultimately causes the change in sign for the torque density in the $y$-direction. As the torque depends on the gradients in $\gamma$ and $\beta$, these small differences will quickly accumulate and feedback on each other, leading to the strikingly different warp evolutions seen in the two calculations.

4 DISCUSSION

4.1 Observational Implications of Burst Driven Warps

The high luminosities of X-ray bursts are necessary for generating warps at moderate disc radii during the burst. In addition, this luminosity must be sustained for several seconds or minutes in order to drive a warp (Fig. 1). Therefore, we expect the highest probability for observing signatures of disc warps in IMDBs or superbursts. However, we also find that the growth of a warp significantly depends on the strength of the viscosity in the disc. Assuming isotropic viscosity, neither Type I bursts nor IMDBs were able to generate a disc warp when $\alpha = 0.05$, while both situations yielded warps when $\alpha$ was doubled (see Figs. 4 and 8). Numerical simulations of accretion discs with viscosities caused by the magneto-rotational instability (Balbus & Hawley 1991, 1998) find that the effective $\alpha$ is both $<0.05$ and varies with both position and time in the flow (e.g., Davis et al. 2010; Bodo et al. 2014; Ryan et al. 2017). These results imply that radiatively driven warps during bursts may be rare and only occur when the exact combination of viscosity, luminosity and duration is obtained at a particular location in the disc. Alternatively, observations of accretion outbursts in binaries suggest that values of $\alpha \approx 0.1$ may be common in ionized accretion discs (see the review by Martin et al. 2019a). In this case, disc warps would develop regularly during X-ray bursts, including many Type I bursts. As X-ray bursts are frequently detected from over 100 binaries in our Galaxy, detailed observations with a high-throughput X-ray telescope such as STROBE-X (Ray et al. 2019) would quickly be able to determine if such values of $\alpha$ occur in NS accretion discs.

The evolution calculations revealed two different types of warping behaviors that depend on the initial warp given to the accretion disc. First, we find ‘pulsations’ of warp concentrated in the inner disc (within $\sim 50 r_g$) that grow and dissipate on timescales of $\sim 1$ s (e.g., Figs. 5 and 9). These pulsations can appear during the plateau phase of the burst and in the tail when the luminosity is decreasing. The growth and decay timescale of $\sim 1$ s are consistent with the radial and vertical diffusion timescales in the disc (Fig. 7). The second behavior found in the calculations is a more slowly growing and larger scale warp that covers a large fraction of the disc (Fig. 12). This warp steadily grows during the plateau phase of the burst before fading during the tail.

These two warp behaviors provide possible explanations for the unusual properties observed in some IMDBs and superbursts. In particular, consider the achromatic variations observed in the tail

Figure 7. The radial profiles of the three different timescale relevant to a warped accretion disc: radial diffusion (Eq. 28, solid lines), vertical diffusion (Eq. 28, dashed lines), and advection (at $t = 0$, Eq. 29, dotted lines). Timescales for calculations with $\alpha = 0.1$ are shown in black while red lines indicate the results for $\alpha = 0.05$. 

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Figure 8. As in Fig. 4, but now for the longer IMDB. Consistent with the analytical expectations (Fig. 1) and similar to the Type I burst, the IMDB does not cause a warp to grow in a disc with $\alpha = 0.05$. When $\alpha = 0.1$, roughly periodic growth and decay of warps occur at $r \lesssim 50 \, r_g$ during the plateau of the IMDB. The pulses of warp occur at intervals of $\approx 3–4$ s and can exceed $\Psi = 1$, indicating they are entering the non-linear regime. The longer duration between pulses is more consistent with the radial diffusion timescale (Fig. 7). The warping is concentrated during the high-luminosity plateau of the burst with only one significant pulse occurring during the tail of the IMDB (at 70.4 s).

Figure 9. As in Fig. 5, but now for the IMDB calculations. The maximum disc warp amplitude ($\Psi = 1.45$) in the $\alpha = 0.1$ model occurs at $t = 38.1$ s and $r = 13 \, r_g$ during the plateau of the IMDB. As in the Type I burst, the warps peak at small radii, within $\sim 20 \, r_g$. 
**Figure 10.** As in Fig. 6, but now for the longer IMDB. The maximum disc tilt during the \( \alpha = 0.1 \) calculation is 10.5 degrees at \( t = 58.5 \) s into the burst. The warp is concentrated at the innermost regions of the disc, peaking at \( r = 9 \, r_g \).

**Figure 11.** As in Figs. 4 and 8, but now showing the \( \alpha = 0.1 \) results when the initial disc twist is \( \gamma_i/2 \) (see Fig. 2). The initial disc tilt is unchanged and equal to \( \beta_i \). For both types of bursts, this simple change in the starting conditions leads to a qualitatively different evolution of disc warp. The pulses of warp concentrated at \( r \lesssim 50 \, r_g \) are now absent and are replaced with a slower growing warp spread over the entire disc. The warp amplitude increases steadily during the plateau of both bursts, before declining during the burst tail. With these conditions, a burst lasting \( \sim 1000 \) s (such as a superburst) would drive a significant warp over a large fraction of the disc.
of the IMDBs from 2S 0918-549 (in’t Zand et al. 2005, 2011), IGR J17062-6143 (Degenaar et al. 2013) and GRS 1741.9-2853 (Barrière et al. 2015). In all these systems, the X-ray lightcurve began showing fluctuations to higher and lower fluxes during the tail of the bursts. The fluctuations were not periodic, but typically had timescales of \( \sim 1 \) s. The scale of the fluctuations was a factor of a few, with the dips tending to be deeper than the enhancements. The changes were observed to be achromatic, indicating that it was not related to Compton-thin absorption by ionized gas. Crucially, in all cases the fluctuations stopped on timescales of \( \sim 1 \) minute and the lightcurves resumed their normal decline. Many of these properties appear to be consistent with the warp ‘pulsations’ found in the previous section. In two-dimensions, these warps will form spiral structures in the disc (e.g., Pringle 1997) that could both block the view of the NS surface (when on the front side) and increase the reflecting surface (when on the back side). As the surface density increases in these warps (e.g., Fig. 4), this would explain the achromatic nature of the fluctuations. The critical dependences on duration, viscosity and luminosity would also be a natural explanation for why these fluctuations only appear in luminous IMDBs, but also their rare and temporary appearance in the burst tails.

It has been noted that the fluctuations only appear in IMDBs that show evidence for super-expansion, where a shell of material is blown off the photosphere for hundreds or thousands of km, and the fluctuations could result from the interaction of the shell with the accretion disc (in’t Zand et al. 2011). However, the burst from GRS 1741.9-2853 which demonstrated fluctuations only had a mild PRE phase with no evidence for super-expansion (Barrière et al. 2015). Therefore, the apparent correlation with super-expansion may be a result that disc warping and a strong PRE phase are both more likely with high luminosity bursts.

The slower, larger scale warp evolution observed in the calculations could explain the high reflection fractions and absorbing column densities found in the spectral analysis of the superbursts from 4U 1820-30 (Ballantyne & Strohmayer 2004) and 4U 1636-53 (Keek et al. 2014b). These two quantities were found to be enhanced thousands of seconds into the burst, well into the burst tail. If a warp steadily grew across the disc during the burst, similar to what is seen in Fig. 11, then it could have reached a point where sufficient ma-
terial was brought into the line of sight to increase the absorbing column density. In addition, the solid angle subtended by the disc would have grown due to the warp, strengthening the total reflection signal in the observed X-ray spectra. in’t Zand et al. (2011) reported that the 4U 1820-30 superburst also displayed achromatic fluctuations late in the burst (at $t \approx 6300-6700$ s), coincident with the increase in column density found by Ballantyne & Strohmayer (2004). Given their long duration, it would not be unexpected for superbursts to have the highest chances of developing radiation driven disc warps.

4.2 Caveats and Directions for Improvement

The results presented in Sects. 2 and 3 show that X-ray bursts from neutron stars are capable of driving temporary warps in their surrounding accretion discs. The existence, evolution and observational consequences of the warps depend on several factors, including the disc viscosity, any initial warp prior to the burst, the burst luminosity, and its duration. While compelling, it is important to recognize the limitations of our proof-of-concept approach, in particular with the evolution calculations of Sect. 3, which, due to the assumption of isotropic viscosity (i.e., $\alpha_2 = 1/2\alpha$) are valid only for small warps ($\Psi < 1$) growing in the linear regime. As noted above, some of our results exceed $\Psi \approx 1$ and should be treated with caution. Appendix A and B present tests of how sensitive our results are to the numerical method. Below, we discuss other issues that could be improved upon in future work.

The development of the equations used in Sects. 2 and 3 focused on radii far from the inner boundary of the accretion disc. However, warps often developed or were transported to small radii, where that approximation would no longer be valid. Moreover, relativistic effects will impact the gravitational potential and orbital velocity profile of gas close to the NS. These effects were also not considered by the calculation. The intrinsic one-dimensional nature of the model is also a limitation, as the warps are known to develop a spiral structure (Pringle 1997) due to differential rotation in the disc. It is also worth noting the razor-thin nature of the disc assumed in the model. It is possible that a disc with a realistic thickness, illuminated from both sides, may have a qualitatively different warping behavior than discussed above.

Clearly, additional numerical simulations of radiated accretion discs that relax one or more of the above assumptions would be valuable tests of the results presented here. The long timescale of the disc warping instability may prove to be prohibitive for detailed global calculations. Therefore, semi-analytical work, similar to this work, will remain valuable when considering radiation driven disc warps. The broad agreement between the analytic estimates of Sect. 2 and the evolution calculations of Sect. 3 indicate that the physical mechanisms underlying radiatively driven warps is likely to be robust and therefore relevant for X-ray bursts and other explosive phenomena with surrounding accretion discs.

5 CONCLUSIONS

The strong radiation field from X-ray bursts can significantly alter many properties of the surrounding accretion disc during the burst (e.g., Degenaar et al. 2018; Fragile et al. 2020). In this paper we demonstrate that bursts can also generate radiatively driven warps in discs. Disc warps will be easier to produce for luminous, long duration bursts (Fig. 1), and therefore we expect signatures of warping to be more common during IMDBs and superbursts, especially those with PRE events, which reach the highest luminosities. Additionally, the ability for a warp to grow depends on the strength of the disc viscosity, with warps being more likely if $\alpha \gtrsim 0.1$. Given the dependence on viscosity, it is possible that warps may be a relatively rare or short-lived occurrence during an IMDB or superburst. However, if evidence for warps is found regularly during Type I bursts then this would indicate that $\alpha \gtrsim 0.1$. Such an investigation would be well within the capabilities of the STROBE-X mission concept.

We considered the evolution of a burst-driven warp in the linear regime due to a Type I burst (lasting 25 s) and IMDB (lasting 250 s) and found two different behaviors for the warps, depending on the initial warp seeding the disc. In some models, rapid (~ 1 s) pulsations of warp growth and decay were found in the inner regions of the disc ($r \lesssim 50 r_g$) during both the plateau and tail of the bursts (Figs. 4 and 8). The timescale of the pulsations were consistent the radial and vertical diffusion times of the disc. The properties of these stochastic warps appear to be consistent with the achromatic fluctuations observed in the tails of several IMDBs (e.g., in’t Zand et al. 2011; Degenaar et al. 2013; Barrière et al. 2015), and provide a natural explanation for their timescales, appearance and disappearance. In the second scenario, the disc developed a more slowly growing warp covering a large fraction of the disc. The growth of the warp was proportional to the duration of the burst, implying that superbursts could develop significant warps over a wide range of radii. This behavior could explain the large reflection fractions and absorbing column densities seen late in the superburst spectra from 4U 1820-30 and 4U 1636-53 (Ballantyne & Strohmayer 2004; Keek et al. 2014b).

Although idealized, the calculations presented here show that radiatively driven accretion disc warps could be a natural consequence of X-ray bursts. This is yet another illustration of how the interaction of bursts with accretion discs presents an unique opportunity to probe accretion processes with a repeatable experiment. As the growth of the warps depend on the viscosity acting in the disc, they provide a potentially important method to observationally constrain the viscous processes within accretion flows. Future work is needed to extend the proof-of-concept studies of this paper and predict observationally testable properties of burst driven disc warps.

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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APPENDIX A: WARP EVOLUTION WITH FREE INNER BOUNDARY CONDITION

One of the assumptions described in Sect. 3.2 is that the disc tilt and twist angles, $\beta$ and $\gamma$, are set to zero at the inner boundary to account for the probable effects of the disc meeting a boundary layer at the NS surface. There is enough uncertainty, however, in the details of the transition to consider the case where $\beta$ and $\gamma$ are not forced to zero at the boundary. Figure A1 shows the results for this situation for a Type I burst impacting a disc with $\alpha = 0.1$. This figure should be compared with the right side of Fig. 4.

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Figure A1. Results of the warp evolution calculation for a Type I burst with $\alpha = 0.1$ when $\beta$ and $\gamma$ are not set to zero at the inner boundary (however, the $\partial \ell / \partial r = 0$ condition remains at the inner boundary). This result should be compared with the right-side of Fig. 4.
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decay phase of the burst. Unlike the situation with $\beta = \gamma = 0$ at the inner boundary, warps grow both at $\sim 25 r_g$ and also at $\sim 90 r_g$. However, pulsations of warp at $\lesssim 1$ s long timescales still occur at both locations. The disc tilt at the inner edge varies throughout the burst, reaching a maximum of 11.1 degrees at 8.1 s. The warps become strongly non-linear, with $\Psi = 5.2$ at 11.1 s and 65 $r_g$, and $\Psi > 1$ at $t \sim 7$–8 s. The surface densities at $r < 25 r_g$ also increase markedly during the periods of non-linear warps. We conclude that the $\beta = 0$ and $\gamma = 0$ boundary condition used in the paper produces a less extreme result that remains safely in the linear regime.

APPENDIX B: RESOLUTION CHECK

The results presented in the paper are calculated on a radial grid from 3 to 401 $r_g$ with $\Delta r = 2 r_g$. The linear nature of the grid was chosen because, a priori, it was unknown where in the disc any warp would start to develop. Indeed, the predictions of Fig. 1, suggested a warp radius of $\sim 100 r_g$, as was found in Fig. 11. To examine the effects of the resolution of the grid, in particular on the properties of the small-scale warp ‘pulsations’ seen in Figs. 4 and 8, we show in Figure B1 the results from repeating the $\alpha = 0.1$, Type I burst calculation with the resolution doubled to $\Delta r = 1 r_g$. Comparing this result to the one shown in the right-hand side of Fig. 4 shows that warp pulsations are still predicted during the plateau phase of the burst, but the ones in the tail do not appear in the $\Delta r = 1 r_g$ calculation. However, the pulsations seen in Fig. B1 are more frequent and stronger during the plateau phase of the burst. The warp peaks are separated by $\sim 1.5$ s, consistent with the radial diffusion time at the inner edge of the disc (Fig. 7). Three of the pulsations exceed $\Psi = 1$, with the last one reaching $\Psi = 2.2$ (corresponding to a $\beta = 5.6$ degrees) at $t = 13.1$ s, indicating that the disc warps are more likely to reach the non-linear regime in higher-resolution simulations. Overall, we conclude that, while the details may change, rapid pulsations of disc warp remain a possible outcome of radiatively driven warps by X-ray bursts. Higher resolution calculations, using, e.g., geometric spacing, are needed to follow the warps into the non-linear regime and will be pursued in future work.

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Figure B1. Results of the warp evolution calculation for a Type I burst with $\alpha = 0.1$ when the resolution of the radial grid is doubled to $\Delta r = 1$. This result should be compared with the the right-side of Fig. 4.