One for the Future: measuring the mass transfer rate in the ULX M82 X-2 by using orbital period changes will take millenia

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ABSTRACT

Bachetti et al. (2021) have recently claimed to measure the mass transfer rate in the pulsing ULX system M82 X-2 by following the change of its orbital period over 7 yr. We reiterate the known point that this method cannot give a reliable result (or even necessarily predict the correct sign of long–term period change) without a far longer baseline (here \(\gg 1000\) yr) or for systems with a much higher long–term mass transfer rate (\(\gg 10^{-4}\)M\(_{\odot}\) yr\(^{-1}\)), if they exist. Applying the method of Bachetti et al. (2021) to measured orbital period derivatives predicts that the well–studied quiescent X–ray transients XTEJ1118+480, A0620–00 should currently instead have steady accretion discs and be bright X–ray sources, while Nova Muscae 1991 should be still brighter (a ULX). But all three sources are observed to be extremely faint. We conclude that there is no evidence to support the high mass transfer rate that Bachetti et al. (2021) find for M82 X-2 as it is deduced from period noise not related to the binary evolution.

Key words: stars: mass-loss – binaries: close – X-rays: binaries – neutron stars – pulsars: general – X-rays: individual: M82 X-2

1 INTRODUCTION

Bachetti et al. (2021) have recently claimed to find a mass transfer rate \(\sim 10^{-6}\)M\(_{\odot}\) yr\(^{-1}\) in the pulsing ULX (or PULX) system M82 X-2 (Bachetti et al. 2014) by measuring the change of its orbital period over 7 years. This claim is based on the standard description of the long–term evolution of a mass–transferring binary system (see e.g. King 1988; Tauris & van den Heuvel 2010 and Frank, King, & Raine 2002 (Section 4.4), for reviews). This uses the equations for conservation of mass and angular momentum for a semidetached binary system, where one star (the mass donor, here denoted as star 2, with mass \(M_2\)) fills its Roche lobe and transfers mass to the other star (star 1). In the system M82 X-2 star 2 is probably an OB giant, and star 1 is a magnetic neutron star.

2 BINARY EVOLUTION

Standard formulae (e.g. Frank, King, & Raine 2002) for the size of the donor’s Roche lobe, together with its mass–radius relation and Kepler’s laws, give relations of the form

\[
\frac{M_2}{M} \sim \frac{\dot{R}_2}{R_2} \sim \frac{\dot{P}}{P} \sim \frac{1}{t_{\text{evol}}},
\]

between the mass transfer rate \(-\dot{M}_2 > 0\), the radius change \(\dot{R}_2\), the orbital period change \(\dot{P}\) and the binary evolution timescale \(t_{\text{evol}}\). This is given by the stellar evolution of the donor (as is likely in M82 X-2, where this star is probably an OB giant like the progenitor of Cyg X-2, cf King & Ritter 1994) or systemic loss of orbital angular momentum. Both \(R_2\) and \(P\) can have either sign depending on what process is driving the evolution, and also the binary mass ratio.

The physical quantity of most interest in studying any interacting binary is the mass transfer rate \(-\dot{M}_2\), but this is frequently hard to measure directly. Then the relations make it tempting instead simply to measure the period evolution \(\dot{P}/P\), and deduce \(-\dot{M}_2\) by using an estimate of \(M_2\), and this is what Bachetti et al. (2021) attempt.
But the vital point missed by a long line of authors, of whom Bachetti et al. (2021) are the latest, is that these equations hold only when averaged on timescales significantly longer than the time

$$t_{\text{H}} = \frac{H}{|R_2|}$$

for the Roche lobe radius to move one density scaleheight $H$ through the donor star.

This requirement comes about because a star does not have a sharp edge ($H = 0$) so cannot be arbitrarily sensitive to very slow secular changes caused by stellar evolution or orbital angular momentum losses. Moreover in deriving (1) it is generally assumed (usually tacitly) that the star is in hydrostatic equilibrium throughout, has no surface magnetic fields, does not lose mass and angular momentum through stellar winds, is not irradiated by the accretor, and is always kept in complete synchronous rotation by tides.

It is likely that none of these assumptions holds in detail – for example the hydrostatic assumption is clearly incorrect precisely where it is needed, near the inner Lagrange point $L_1$, as the star is losing mass at about its local sound speed there. So directly observed period changes are actually dominated by large but short-term effects, such as variations in the stellar mass loss, oscillations of the stellar envelope, mass currents in the donor driven by irradiation, or magnetic cycles causing slight radius changes. Most of these have no effect on the mass transfer rate – $\dot{M}_2$. They may be oscillatory and average out, but in all cases are eventually dwarfed by the systemic binary evolution on timescales $\tau_{\text{vol}} \gg t_{\text{H}}$.

The star’s gas density $\rho$ near $L_1$ can change exponentially ($\rho \propto e^{\mp \tau_{\text{vol}}/t_{\text{H}}}$) on this timescale, the sign depending on whether the binary separation grows or shrinks over time). This supplies the ‘sharp edge’ forcing $\langle \dot{M}_2 \rangle$, $\langle R_2 \rangle$, $\langle P \rangle$ and their time derivatives averaged on timescales $\gg t_{\text{H}}$ to obey the relations (1).

This point has been made repeatedly in the literature, going back at least to Pringle (1975); see also e.g. Ritter (1988) and Frank et al., (2002, Section 4.4). As an indication of the difficulties involved here, it is common for observed short-term period changes even to have the wrong sign for the claimed long-term evolution (cf Pringle 1975).

3 THE ULX M82 X-2

For an OB giant we have

$$H \approx \frac{k T r_2^2}{G M_2 m_2} \approx 5 \times 10^7 T_4 r_2^2 m_2^{-1} \text{cm},$$

where $M_2 = m_2 M_\odot$, $r_2 = r_2 R_\odot$ are the donor mass and radius and $T_4$ its effective temperature in units of $10^4$ K. In fact $H$ is somewhat larger than this near the inner Lagrange point, where the mass transfer takes place.

Then to find orbital period changes consistent with the claimed mass transfer rate in M82 X-2, one would need to observe the for a time

$$t \gg t_{\text{H}} = \frac{H}{R_2} = \frac{H_2 R_2}{R_2} = \frac{H_2}{R_2} \tau_{\text{vol}} \gg \frac{10^9 T_4 r_2}{m_2} \text{yr} > 1000 \text{yr}$$

(4)

(where we have adopted Bachetti et al. (2021)’s value $T_4 R_2 / R_2 \approx 10^8 \text{yr}^{-1}$) rather than 7 yr. For a smaller and probably more realistic binary evolution rate, $\tau_{\text{vol}}$ is even longer, so the required observation time is still more protracted.

4 TESTING THE METHOD

Bachetti et al. (2021) do not give details of any test of their method by using publicly available data on orbital period changes in mass-transferring binaries. Three well-studied X-ray transients (Nova Muscae 1991, XTE J1118+480, A0620–00), all currently in the faint quiescent state, have significant orbital period changes ($-6.56 \times 10^{-10}$, $-6.01 \times 10^{-11}$, $-1.9 \times 10^{-11}\text{yr}^{-1}$, respectively; Gonzalez Hernandez et al. 2017), and so offer a clear test.

Following the argument of Bachetti et al. (2021) these data lead (cf eqn (1)) to mass transfer rates in the range

$$-\dot{M}_2 \approx \frac{\dot{P}}{P} M_2 \approx 8.5 \times 10^{-9} - 4.8 \times 10^{-7} \text{M}_\odot \text{yr}^{-1}.$$  (5)

These are significantly above the values required to make the accretion disc in all three systems steady, in the high state where hydrogen is ionized, rather than quiescent and occasionally producing transient outbursts. So they should have bright persistent luminosities $5 \times 10^{37} - 3 \times 10^{39} \text{erg s}^{-1}$ (Nova Muscae 1991 would be a ULX!). Yet observation show that all three systems remain extremely faint.

5 CONCLUSION

As we have reiterated above, even a millenium is far too short a time to determine the mass transfer rate from orbital period changes in any stellar–mass binary, and M82 X-2 is no exception. “... an accurate estimate of the rate of mass transfer cannot be deduced from a change of binary period” (Pringle 1975). Clear tests of the method of Bachetti et al. (2021) using data on period changes in soft X–ray transients give extremely discouraging results. We conclude that mass transfer value claimed by Bachetti et al. (2021) is physically meaningless as it is deduced from period noise.

Bachetti et al. (2021) draw far-reaching conclusions from this claim, in particular that all PULXs have a unique and isolated neutron star magnetar–strength magnetic field. But some PULXs are actually ordinary Be/X–ray binaries when not in particularly bright outbursts, and there is no evidence for such fields in Be/X–ray binaries.

King & Lasota (2019) have shown instead that the properties of M82 X-2 are consistent with a neutron star

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1 The orbital periods of cataclysmic variables (CVs) are easy to find as they are only a few hours. Several hundred are now known, but it is well understood in that field that one cannot safely deduce mass transfer rates from them.

2 They are transferring mass at much lower rates (Coriat, Fender, & Dubus 2012), filling the quiescent accretion disc before its next outburst.
magnetic field $10^{10} - 10^{11}$ G, a mass transfer rate $\sim 50$ times the Eddington value, and beaming factor $b \sim 0.03$ (see also King, Lasota & Middleton 2022). This agrees with the deduction that observed ULXs are ordinary high-mass X-ray binaries in a special stage of their binary evolution (King et al. 2001; Wiktorowicz et al. 2017).

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