# An ultraluminous nascent millisecond pulsar.

W. Kluzniak, J. -P. Lasota

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **448,** L43–L47 (2015) doi:10.1093/mnrasl/slu200

# An ultraluminous nascent millisecond pulsar

Włodek Kluźniak[1★] and Jean-Pierre Lasota[1,2,3]
[1]Copernicus Astronomical Center, ul. Bartycka 18, PL 00-716 Warszawa, Poland
[2]CNRS, UMR 7095, Institut d'Astrophysique de Paris, 98bis Bd Arago, F-75014 Paris, France
[3]Sorbonne Universités, UPMC Univ Paris 06, UMR 7095, 98bis Bd Arago, F-75014 Paris, France

Accepted 2014 December 11. Received 2014 November 24; in original form 2014 November 4

## ABSTRACT

If the ultraluminous source (ULX) M82 X-2 sustains its measured spin-up value of $\dot{\nu} = 10^{-10}\ \mathrm{s}^{-2}$, it will become a millisecond pulsar in less than $10^5$ yr. The observed (isotropic) luminosity of $10^{40}\ \mathrm{erg\ s}^{-1}$ also supports the notion that the neutron star will spin up to a millisecond period upon accreting about $0.1\ \mathrm{M}_{\odot}$ – the reported hard X-ray luminosity of this ULX, together with the spin-up value, implies torques consistent with the accretion disc extending down to the vicinity of the stellar surface, as expected for low values of the stellar dipole magnetic field ($B \lesssim 10^9$ G). This suggests a new channel of millisecond pulsar formation – in high-mass X-ray binaries – and may have implications for studies of gravitational waves, and possibly for the formation of low-mass black holes through accretion-induced collapse.

**Key words:** accretion: accretion discs – gravitational waves – magnetic fields – stars: black holes – stars: neutron – pulsars: individual: NuSTAR J095551+6940.8.

## 1 INTRODUCTION

The unexpected discovery of a 1.37 s pulsation in the M82 X-2 ultraluminous source (Bachetti et al. 2014) invites a reevaluation of common assumptions about the nature of ultraluminous sources (ULXs) and the evolutionary paths of pulsars.

ULXs were universally considered to be accreting black holes, most likely $\sim 10\,\mathrm{M}_{\odot}$ ones in a binary with a high-mass companion, with some sources possibly harbouring 'intermediate-mass' $\sim 10^{2-3}\,\mathrm{M}_{\odot}$ black holes (King et al. 2001; Roberts 2007). Their high luminosity was thought to imply that if the X-ray source is of typical stellar mass, the emission should be beamed, perhaps in an accretion funnel.

*Chandra* discovery of a population of ULXs with lifetimes $\lesssim 10^7$ yr in the Cartwheel galaxy suggests that ULXs should be high-mass X-ray binaries (HMXBs; King 2004), so $\sim 10\ \mathrm{M}_{\odot}$ black holes seemed to be the preferred model. However, not all HMXBs are black hole systems: (non-ULX) binaries composed of a neutron star and a massive stellar companion are routinely observed, both in detached systems (e.g. Be binaries; Reig 2011) and semidetached systems (accretion powered X-ray pulsars; van Paradijs & McClintock 1995).

Bachetti et al. (2014) report a $P = 1.37$ s pulsar in M82 X-2, which is spinning up at the rate $\dot{P} = -2 \times 10^{-10}$, and whose emission shows a 2.5-d sinusoidal modulation, interpreted as the orbital motion of the X-ray source revolving around a $>5\,\mathrm{M}_{\odot}$ companion. Clearly, this ULX is a neutron star HMXB. Only a few weeks earlier, a nearby source M82 X-1 was reported to exhibit a 5 Hz frequency, interpreted at the time as a high-frequency QPO in an $\sim 400\,\mathrm{M}_{\odot}$ black hole (Pasham, Strohmayer & Mushotzky 2014); one wonders whether the 5 Hz frequency could instead have been a harmonic of a 0.6 s pulsar, so that both ULXs in M82 might be harbouring a neutron star. If, instead, M82 X-1 is indeed an intermediate-mass black hole, one would expect the similarity of X-ray properties of the two sources to imply that the non-pulsed emission from M82 X-2 originates in the accretion disc, as it must in the (presumed) black hole M82 X-1.

In their discussion, Bachetti et al. (2014) assume the pulsar NuSTAR J095551+6940.8 to be a run-of-the-mill accretion-powered neutron star pulsar endowed with a $10^{12}$ G magnetic field (dipole moment $\mu = 10^{30}\ \mathrm{G\,cm}^3$). In our view, such an assumption is difficult to reconcile with the data. A dipole moment this strong would disrupt the accretion disc at a large distance (about 100 stellar radii) from the neutron star. However, while the measured spin-up rate is uncommonly high, the ratio of the measured value of the frequency derivative to the luminosity ($L_X \approx 10^{40}\ \mathrm{erg\ s}^{-1}$) is incompatible with a large lever arm of the accretion torque typical of X-ray pulsars (such as Her X-1), where the lever arm corresponds to the magnetic radius $\sim 10^8$–$10^9$ cm. Moreover, for an inner disc radius so large, the disc emission would be in soft X-rays, implying that on this hypothesis the hard X-ray luminosity observed by *NuSTAR* cannot originate in the accretion disc – the observed luminosity would have to originate in the polar accretion column close to the neutron star surface, making any similarity of the unpulsed X-ray emission to that of black hole ULXs purely fortuitous.

Future observations will show whether the current spin-up rate is secular. However, at present there is no compelling reason to assume that the large spin-up torques present in the system today are going to be displaced by equally large spin-down torques in

★ E-mail: wlodek@camk.edu.pl

the foreseeable future. If the current properties of the system were extrapolated into the future, one would conclude that the pulsar will be spun up to millisecond periods already upon accreting $\sim$0.1 $M_\odot$, which is a small fraction of the donor star's mass.

At the current spin-up rate, $\dot{\nu} = -\dot{P}/P^2 = 10^{-10}\,\mathrm{s}^{-2}$, the ultraluminous pulsar would become a millisecond pulsar in less than 100 000 yr: $\nu = T\dot{\nu} = 300\,\mathrm{Hz}$ in $T = 10^5$ yr. Subsequent evolution of the system depends on how successful the neutron star is in expelling the mass and angular momentum transferred from the companion – the system could become a millisecond accreting pulsar, it could become a radio pulsar ablating its companion (a 'black widow' progenitor), or it could end as a black hole binary, possibly a ULX, upon accretion induced collapse of the neutron star.

## 2 SPINUP OF THE ULTRALUMINOUS PULSAR M82 X-2

A remarkable feature of ULXs is, of course, their large luminosity. It is even more remarkable now that the compact source has been identified as a pulsar, as this would imply an $\sim$1.4 $M_\odot$ mass and an apparent (isotropic) luminosity a hundred times the Eddington value, $L_X \approx 10^2 L_{\mathrm{Edd}}$. However, for this ULX pulsar the most striking feature is its measured spin-up rate. On the one hand, in absolute terms, the spin-up rate $\dot{\nu} = 10^{-10}\,\mathrm{s}^{-2}$ is orders of magnitude higher than the values measured in the usual accretion powered X-ray pulsars, e.g. $3.7 \times 10^{-13}\,\mathrm{s}^{-2}$ in Her X-1, or $7 \times 10^{-12}\,\mathrm{s}^{-2}$ in Cen X-3 (Bildsten et al. 1997; Ziółkowski 1985). On the other hand, the spin-up to luminosity ratio $10^{-50}\,(\mathrm{erg\,s})^{-1}$ is an order of magnitude lower than the typical ratio observed in the X-ray pulsars.

It is this ratio, $\dot{\nu}/L_X = 10^{-50}\,(\mathrm{erg\,s})^{-1}$, which makes an interpretation of the data in terms of a strongly magnetized X-ray pulsar quite challenging. One would need to find a model in which the accretion disc, even though truncated[1] close to the corotation radius at the current period (at $r \approx r_{\mathrm{co}} = 2 \times 10^8$ cm), would be very luminous in hard X-rays but relatively little mass were accreted on to the neutron star (so that the torque be low). One difficulty with such a scenario is purely empirical: the effective temperature (Shakura & Sunyaev 1973) of such a disc, $T \approx [L_D/(\sigma\pi r_{\mathrm{co}}^2)]^{1/4}$ should be one-third the value of the temperature for an Eddington luminosity disc extending to the surface of the neutron star, i.e. no more than 1 keV. The large flux observed by *NuSTAR* in the 3–30 keV range makes this unlikely.

Further, to have most of the luminosity coming from the disc with an inner edge at approximately $r_{\mathrm{co}} = 2 \times 10^8$ cm, one would have to have a model in which the mass accretion rate[2] through the disc terminating at $\sim$100 stellar radii from the neutron star, $\dot{M}_D \gtrsim L_D r_{\mathrm{co}}/(GM)$, would have to be $>10^4$ the Eddington value (for $L_D \approx 10^2 L_{\mathrm{Edd}}$), corresponding to a mass transfer rate from the companion $>10^{-4}\,M_\odot\,\mathrm{yr}^{-1}$.

In view of these difficulties, we will start our discussion of the spin-up torques by examining the most conservative model of NuSTAR J095551+6940.8, a disc extending essentially to the surface of the neutron star.

[1] So that, according to the criticized model, in the near future the torque on the neutron star could undergo a reversal of sign owing to magnetic interactions (Pringle & Rees 1972; Rappaport & Joss 1977; Kluźniak & Rappaport 2007, and references therein).

[2] According to the Shakura & Sunyaev (1973) model (see also King 2009) of super-Eddington discs, the luminosity increases only logarithmically with the mass accretion rate. If this model were applicable to the current situation, $\dot{M}_D$ would have to be much higher than $10^{-4}\,M_\odot\,\mathrm{yr}^{-1}$. On the other hand, this model neglects advection of energy which may play a crucial role in the accretion rate radial distribution (e.g. Sadowski et al. 2014).

## 3 SPIN-UP OF AN ULTRALUMINOUS WEAKLY MAGNETIZED NEUTRON STAR

Neglecting the dynamical influence of magnetic fields (dipole magnetic field at the stellar surface of $\sim 10^9$ G or less), one expects the accretion disc in a semidetached neutron star binary to extend to the surface of the star or to terminate between the marginally stable and marginally bound orbit, depending on the accretion rate and the compactness of the star.

Let us estimate the expected isotropic emission $L_X$ associated with the spin-up rate of the neutron star in such a situation, assuming canonical neutron star parameters: mass $M = M_0 \equiv 1.4\,M_\odot$, radius $R = R_0 \equiv 10$ km and moment of inertia $I = I_0 \equiv 10^{45}\,\mathrm{g\,cm}^2$. In the next section we will place constraints on these parameters derived from the observed properties of M82 X-2.

For a slowly spinning pulsar, the Schwarzschild metric is an excellent approximation, and as the marginally stable orbit (ISCO) is at $r_{\mathrm{ms}} = 6GM_0/c^2 = 13\,\mathrm{km} > R_0$, we can take the rate of accretion of angular momentum to be

$$\dot{J}_0 \equiv \dot{M}c \times r_{\mathrm{ms}}/\sqrt{3}, \tag{1}$$

assuming Keplerian motion in the marginally stable orbit. Here, and elsewhere, $\dot{M}$ is the mass accretion rate on to the neutron star. The related spin-up rate is

$$\dot{\nu}_0 = \frac{\dot{J}_0}{2\pi I_0}. \tag{2}$$

Taking $\dot{\nu}_0 = \dot{\nu} = 10^{-10}\,\mathrm{s}^{-2}$, we obtain $\dot{M} = 0.3 \times 10^{20}\,\mathrm{g\,s}^{-1} \approx 0.5 \times 10^{-6}\,M_\odot\,\mathrm{yr}^{-1}$ corresponding to the luminosity $L_0 = GM\dot{M}/R_0 = 0.5 \times 10^{40}\,\mathrm{erg\,s}^{-1}$, which compares very favourably with the (isotropic) luminosity inferred from the observations $L_X = 10^{40}\,\mathrm{erg\,s}^{-1}$. We have ignored the modest redshift correction to $L_0$, of magnitude $[1 - 2GM_0/(R_0c^2)] \sim 0.7$, since about one half of the power is released at larger radii in the accretion disc. Thus, we see that the observed luminosity is a direct consequence of mass accretion on to the surface of a neutron star at the rate necessary to explain the spin-up rate with a lever arm approximately equal to the stellar radius.

## 4 NATURE OF THE ULTRALUMINOUS PULSAR M82 X-2

In the previous section, we used canonical values for the neutron star parameters to infer that there is no evidence of a strong magnetic field in the spin-up behaviour of the M82 X-2 source, and no compelling reason to expect the accretion torque to change in the future.

Had we assumed a strong magnetic field that terminates the disc far above the stellar surface (i.e. at $r \gtrsim 100R_0$ for $B \gtrsim 10^{12}$ G), the mass accretion rate corresponding to the same torque would have been lower by a factor $\sim\sqrt{r_{\mathrm{ms}}/r} < 0.1$ decreasing the luminosity released at the surface by a factor of 10. It is hard to see how this deficit in hard X-ray luminosity could be made up by the disc. As remarked in Section 2, at such large distances from the neutron star, the disc should be emitting soft X-rays, at most. In other words, if the disc terminates far above the stellar surface, the mass accretion rate inferred from the luminosity would have been the same (assuming isotropic emission), but the torques would be enhanced by a factor $\sim\sqrt{r/r_{\mathrm{ms}}} > 10$, leading to a spin-up rate much larger than the observed one. One could argue that the accretion torques could be compensated by magnetic torques transmitting angular momentum back to the accretion disc, but it would be an unexplained coincidence that the difference of two larger torques results in a value exactly matching the one corresponding to $r \approx R$.

So far we have ignored possible beaming of radiation. We now allow this possibility with no theoretical prejudice as to its origin. We would like to examine the constraints on the compact source imposed by the observations of the M82 X-2 pulsar. The period alone, $P = 1.37$ s rules out white dwarfs and less compact stars (Thorne & Ipser 1968), and imposes a lower limit to the mean density of the compact object of $\bar{\rho} > 10^8$ g cm$^{-3}$, following from the mass-shedding limit $\sqrt{4\pi G\bar{\rho}/3} > 2\pi/P$. The coherent periodicity obviously rules out black holes. Of the astronomical objects known so far, only neutron stars are compatible with the measured period.

The question is whether we can determine the mass and radius of the (presumed) neutron star, as well as the accretion geometry. The simultaneous measurement of the luminosity of the source and its spin-up is quite constraining, although the radius cannot be determined separately from the mass at present.

For convenience, we will eventually parametrize the effective radius $r$ corresponding to the torque lever arm with the radius of the marginally stable orbit in the Schwarzschild metric, $r_{\rm ms} = 6\,GM/c^2$. Models of neutron stars give stellar radii very close to that value for most equations of state of dense matter (Kluźniak & Wagoner 1985; Cook, Shapiro & Teukolsky 1994), so $r/r_{\rm ms} \approx r/R$. The luminosity expression will differ from the isotropic one by a beaming factor, $b \le 1$ and we will allow redshift corrections $f_1(R) \sim 1$,

$$bL_{\rm X} = f_1(R) GM\dot{M}/R. \tag{3}$$

Here, $bL_{\rm X}$ is the true luminosity. In addition to the 'material' torque corresponding to the advected angular momentum proportional to the product of $\dot{M}$ and of the specific angular momentum of the accreting matter, magnetic torques may be present. The latter may be of either sign, depending on the accretion geometry which is related to $\dot{M}$ and the magnetic dipole moment. Indeed, observations of X-ray pulsars near equilibrium reveal periods of spin-up followed by periods of spin-down at comparable rates (Bildsten et al. 1997). We are going to parametrize the total torque acting on the neutron star by an effective radius corresponding to the total torque divided by the orbital specific angular momentum at that radius times $\dot{M}$:

$$\tau = f_2(r)\sqrt{GMr}\,\dot{M}, \tag{4}$$

with $f_2(r)$ describing relativistic corrections. The specific angular momentum value, $J_0$, for test particles in the marginally stable orbit is recovered with $r = r_{\rm ms}$ and $f_2(r) = \sqrt{2}$. The moment of inertia of the neutron star can be written as

$$I = \beta M R^2, \tag{5}$$

with $\beta \approx 0.3$ (Urbanec, Miller & Stuchlík 2013). Applying the torque to the star,

$$\tau = 2\pi\dot{\nu} I, \tag{6}$$

we obtain

$$MR = \frac{f_2(r)}{\beta c f_1(R)} \frac{bL_{\rm X}}{2\pi\dot{\nu}} \sqrt{\frac{rc^2}{GM}}. \tag{7}$$

Putting $f_2/(\sqrt{6}\beta f_1) \approx 1$ one gets

$$\frac{b^2 r}{r_{\rm ms}} \approx 0.4 \left(\frac{R}{R_0}\right)^2 \left(\frac{\dot{\nu} \times 10^{50}\ {\rm erg\ s}}{L_{\rm X}}\right)^2 \left(\frac{M}{1.4\,{\rm M}_\odot}\right)^2. \tag{8}$$

Several conclusions can be drawn from this equation, which can also be written in the form

$$\frac{r r_{\rm ms}}{R^2} \approx \left(\frac{\dot{\nu} \times 10^{50}\ {\rm erg\ s}}{bL_{\rm X}}\right)^2 \left(\frac{M}{1.4\,{\rm M}_\odot}\right)^4.$$

First, if there is no strong beaming, i.e. $b \sim 1$, applying an accretion torque corresponding to an inner disc radius far above the stellar surface, $r \gg R$, would imply a large mass of the compact star, requiring an exotic model of dense matter. In the standard magnetized accretion powered pulsar models, the value of $r$ is very close to the corotation radius. A constraint on $r$ can then be translated into a corotation frequency, i.e. equilibrium rotation frequency of the pulsar. The largest measured (and already challenging nuclear theorists) neutron star mass (Demorest et al. 2010; Antoniadis et al. 2013) is $M = 2\,{\rm M}_\odot$, for which all theoretical models give $R \ll r_{\rm ms}$. Hence, for standard neutron stars we have an upper limit of $r \ll 5r_{\rm ms}$, corresponding to a corotation frequency of $>100$ Hz $\times$ $(2\,{\rm M}_\odot/M)$.

Secondly, a small value of the beaming factor, $b \ll 1$ could in principle allow large values for the inner radius of the accretion disc, $r \sim b^{-2} r_{\rm ms} \approx b^{-2} R$, but the beaming could not be then provided by the accretion funnel postulated in other ULXs (e.g. King et al. 2001), the disc being here too far from the compact star to collimate the radiation. If one wanted to invoke beaming to reduce the luminosity of the source inferred from the observed flux, it would have to occur near the surface of the star, and yet allow for a large part of the flux to be unmodulated by the rotation of the neutron star.

One could invoke collimation by the magnetic field tube at the pole (perhaps a fan beam caused by radiation escaping sideways from the accretion column in a strong magnetic field; Gnedin & Sunyaev 1973). A beaming fraction $b \sim 10^{-1}$ would increase the magnetic truncation radius of the disc by the requisite factor of 100, and decrease the mass accretion rate inferred from the luminosity by a factor of 10. For the system at hand, this would imply a mass accretion rate $b \times 10^{-6}\,{\rm M}_\odot\,{\rm yr}^{-1} = 10^{-7}\,{\rm M}_\odot\,{\rm yr}^{-1}$ (which could be hard to understand in a system presumably undergoing unstable mass transfer through the Roche lobe, e.g. Tauris, Langer & Kramer 2011). However, to be consistent one should do the same for the ordinary X-ray pulsars, as it would otherwise be hard to see why increasing the luminosity should lead to increasingly beamed emission (lower values of $b$). For the ordinary X-ray pulsars the same beaming fraction, $b = 0.1$, would necessitate increasing the magnetic radius to the impossibly large value $\approx 10^{10}$ cm, and decrease the typical mass transfer rate to $10^{-11}\,{\rm M}_\odot\,{\rm yr}^{-1}$.

Further, there remains an improbable coincidence related to the one mentioned at the end of the second paragraph of this section. We are unaware of any mechanism which would relate the beaming factor to the inverse square root of the magnetic or corotation radius, as required by equation (8): $b \approx (r_{\rm ms}/r)^{1/2}$.

### 4.1 An ultraluminous accreting millisecond pulsar

In view of the difficulties associated with the strongly magnetized pulsar model for NuSTAR J095551+6940.8, and the coincidences required to make it compatible with the observations, it seems much more natural to assume that $b \sim 1$, implying that $M \approx 1.4\,{\rm M}_\odot$, and that the inner disc radius is comparable to the stellar radius $r \sim R \approx r_{\rm ms}$, with no strong upper limits on the future spin frequency of the M82 X-2 neutron star.

The idea that accreting weakly magnetized neutron stars may exhibit pulsations in X-rays is not new, with the first such system, the 400 Hz SAX J1808.4−3658 pulsar, discovered more than a decade ago (Wijnands & van der Klis 1998). Of course, the known accreting millisecond pulsars are not HMXBs, in fact the typical companion mass is $\lesssim 0.1\,\mathrm{M}_{\odot}$. We take it as an empirical fact that accreting weakly magnetized neutron stars become X-ray pulsars under some conditions, presumably channelling a large part of the accretion flow to the magnetic poles. What these conditions need to be is an open theoretical question. Many LMXBs have accretion rates which are a large fraction of the Eddington limit value, and some of them exhibit transient pulsations (Galloway et al. 2007; Altamirano et al. 2008; Casella et al. 2008). At present, it is not known why millisecond accreting pulsars do not always exhibit their periodicity (pulsations), and whether this is related to the mass accretion rate. In particular, it is not known whether rapid rotation plays a role in the suppression of pulsations, i.e. whether or not weakly magnetized neutron stars are more likely to exhibit pulsations when rotating slowly.

Assuming that our suggestion of low magnetic field in the source is correct, is there any way for NuSTAR J095551+6940.8 to avoid being spun up to millisecond periods? The neutron star could not yet have accreted more than a small percentage of a solar mass (about $10^{-3}\,\mathrm{M}_{\odot}$ judging by its current period of 1.37 s), and will not accrete more than $0.1\,\mathrm{M}_{\odot}$ before it is spun up to hectohertz frequencies. So unless it was formed as an unusually massive ($2\,\mathrm{M}_{\odot}$) object, the neutron star is not going to collapse to a black hole before it becomes a millisecond pulsar.

One difficulty with our model of persistent spin-up is that we seem to be observing the pulsar in the first $10^3$ yr of a $10^5$ yr accretion episode, which on the face of it would correspond to one chance in a hundred. In view of the theoretical uncertainties discussed in the previous two paragraphs it is hard to reliably estimate the selection effects involved, i.e. over what fraction of the $10^5$ yr epoch of mass transfer the pulsar would be detectable (or even exist at all).

Another possible way to avoid spin up is to turn off accretion on to the star. This seems unlikely. With a companion so massive, and such a high luminosity at this orbital period the system is probably undergoing unstable mass transfer through Roche lobe overflow which is going to continue until the companion loses most of its mass. Of course, since the discovery of the first eclipsing pulsars, we know of systems where mass transfer (loss from the companion) occurs with no accretion on to the neutron star; however, this is an unlikely scenario for the binary at hand. Although, perhaps, at some point in time the pulsar could turn on in the radio, (i.e. become a radio pulsar if the mass transfer rate temporarily drops) as predicted theoretically (Kluźniak et al. 1988) and recently observed (e.g. Archibald et al. 2009; Bassa et al. 2014), it would take a very powerful radio pulsar indeed to expel from the system matter transferred at such a prodigious rate. Note that the known eclipsing pulsars that ablate their companions are in fact millisecond pulsars, and their companions have fairly low masses.

### 4.2 Alternative pulsar models

Several authors suggest a different model. Bachetti et al. (2014), Christodoulou, Laycock & Kazanas (2014), Ekşi et al. (2014) and Lyutikov (2014) assume that the M82 X-2 pulsar is close to spin equilibrium, and obtain ∼1–100 TG values for the magnetic field $B$. While this cannot be excluded with the present data (notwithstanding the improbable coincidences discussed above), we note that the assumption of equilibrium spin is notoriously unreliable as a predictor of magnetic dipole strength in massive binaries.

Several Be X-ray binaries exhibit observed cyclotron lines corresponding to a 3 TG field, and yet their periods span 3.5 orders of magnitude (Klus et al. 2014). If assumed to be in torque equilibrium, they should all have the same period, as the adopted torque model gives a one to one correspondence between the magnetic field strength and the equilibrium spin (the luminosity does not vary much from source to source in the sample). In other words, estimates of the magnetic field in the same sample, if based on the assumption that the observed period is the equilibrium one, would lead to the predicted $B$-field value being up to three orders of magnitude larger than the actually measured values (Klus et al. 2014).

## 5 PAST AND FUTURE EVOLUTION OF THE ULTRALUMINOUS PULSAR

The mass of the companion star of the M82 X-2 pulsar is (assuming the neutron star mass $M = 1.4\,\mathrm{M}_{\odot}$) $M_2 > 5.2\,\mathrm{M}_{\odot}$ (Bachetti et al. 2014). To provide the required mass accretion rate $\dot{M} \gtrsim 10^{-6}\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$ the companion has to fill its Roche lobe. Since the ratio of the companion to the neutron star masses is $q \equiv M_2/M > 1$, the mass from the donor will be transferred on its thermal time-scale assuming its envelope is radiative. The evolution of such systems has been studied by King & Ritter (1999, see also King, Taam & Begelman 2000).

If the mass of the companion is not much higher than the lower limit of $5.2\,\mathrm{M}_{\odot}$, the past evolution of the system could be one considered for intermediate-mass X-ray binaries (IMXBs). Generally speaking, no detailed calculation of the magnetic field origin in supernova explosions are available. Perhaps the different evolutionary scenario of HMXBs and of ULXs could be responsible for a lower field value in the M82 X-2 case than in the common HMXBs. Until now IMXBs were a theoretical concept thought unlikely to be observed because of the fairly brief fraction of their lifetime corresponding to episodes of high-mass transfer. However, observation of a ULX selects this very phase of rapid mass transfer. In particular, Case A of Roche lobe overflow of Tauris et al. (2011) corresponds to an $\sim 10^5$ yr epoch of mass transfer in excess of $10^{-6}\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$. The progenitor would have been a $\geq 20\,\mathrm{M}_{\odot}$ primary with a $\geq 5\,\mathrm{M}_{\odot}$ secondary, the high-mass transfer phase occurring ∼100 million years after formation, following a common envelope phase and a supernova explosion, with the system evolving towards a neutron star – white dwarf binary (Tauris et al. 2011), a perfect progenitor for a 'black widow' pulsar ablating its companion (Eichler 1988; Fruchter, Stinebring & Taylor 1988; Kluźniak et al. 1988; Kluźniak, Czerny & Ray 1992), if the pulsar is ever spun up to a millisecond period.

However, because of the relatively high donor mass $M_2 > 5\,\mathrm{M}_{\odot}$ the future of the M82 X-2 binary is difficult to predict since it is unlikely that it will avoid the so-called delayed dynamical instability (e.g. Webbink 1977) when the companion star expands adiabatically in response to mass-loss. In principle, this should force the system to go through a second common envelope phase whose outcome is notoriously uncertain (Ivanova et al. 2013). On the other hand, King & Ritter (1999) notice that 'even very rapid mass transfer on to a neutron star does not necessarily result in a common envelope'.

Therefore, the future fate of the M82 X-2 accreting pulsar is also uncertain, and depends on the mass-loss and angular momentum loss from the system. Mass transfer of only $0.2\,\mathrm{M}_{\odot}$ is in principle sufficient to spin up a weakly magnetized pulsar to 800 Hz, i.e. faster than any observed one, and of $0.3\,\mathrm{M}_{\odot}$ to the mass-shedding limit. If mass transfer continues, the pulsar must lose angular momentum. If it is unable to transfer angular momentum outwards through the disc, or to lose it to a jet, it may become a powerful source of gravitational radiation (Wagoner 1984), until such time as mass accretion stops or, alternatively, the neutron star will collapse to a black hole. In the latter case, a period of $\sim 10^5$ yr of powerful steady emission of gravitational waves would be followed by black hole formation outside a supernova, in an accretion induced collapse, which could lead to a black hole ULX or, depending on the mass ratio of the components at the time of the collapse, possibly unbind the binary yielding a fairly low-mass black hole which could escape the galactic plane, as would the erstwhile companion.

## 6 CONCLUSIONS

A neutron star in an IMXB or an HMXB will be spun up to millisecond periods upon accreting about 0.1 $M_\odot$, if only its magnetic dipole moment is sufficiently low to allow the accretion disc to extend to the stellar radius, or its immediate vicinity. Judging by its apparent luminosity and the measured value of its spin-up, this seems to be the case for the M82 X-2 source, the 1.37 s pulsar NuSTAR J095551+6940.8.

In subsequent phases of its evolution the pulsar must either avoid further accretion of angular momentum or become a powerful source of gravitational radiation. The neutron star may either survive as a millisecond pulsar or collapse to a black hole depending on how effective it is in expelling most of the matter transferred from the massive companion.

Whether or not our suggestion turns out to be true, one needs to entertain the possibility that other ULXs may be pulsars. For instance, the recently reported 3.3 Hz and 5 Hz frequencies in the X-ray flux of M82 X-1 (Pasham et al. 2014) could in fact turn out to be harmonics of 1.67 Hz, i.e. that source may be a $P = 0.6$ s pulsar. Another ULX, in NGC 7793, has an upper limit to the mass of the compact object of $<15\,M_\odot$, with allowed solutions in the neutron star mass range and phenomenology of state transitions similar to that of Her X-1 (Motch et al. 2014).

## ACKNOWLEDGEMENTS

We thank the anonymous referee for the very helpful comments, and Thomas Tauris for discussion. This work was supported in part by the Polish NCN grant UMO-2013/08/A/ST9/00795. JPL acknowledges support from the French Space Agency CNES.

## REFERENCES

Altamirano D., Casella P., Patruno A., Wijnands R., van der Klis M., 2008, ApJ, 674, L45
Antoniadis J. et al., 2013, Science, 340, 448
Archibald A. M. et al., 2009, Science, 324, 1411
Bachetti M. et al., 2014, Nature, 514, 202
Bassa C. G. et al., 2014, MNRAS, 441, 1825
Bildsten L. et al., 1997, ApJS, 113, 367
Casella P., Altamirano D., Patruno A., Wijnands R., van der Klis M., 2008, ApJ, 674, L41
Christodoulou D. M., Laycock S. G. T., Kazanas D., 2014, preprint (arXiv:1411.5434)
Cook G. B., Shapiro S. L., Teukolsky S. A., 1994, ApJ, 422, 227
Demorest P. B., Pennucci T., Ransom S. M., Roberts M. S. E., Hessels J. W. T., 2010, Nature, 467, 1081
Eichler D., 1988, Nature, 336, 557
Ekşi K. Y., Andaç İ. C., Çıkıntoğlu S., Gençali A. A., Güngör C., Öztekin F., 2014, preprint (arXiv:1410.5205)
Fruchter A. S., Stinebring D. R., Taylor J. H., 1988, Nature, 333, 237
Galloway D. K., Morgan E. H., Krauss M. I., Kaaret P., Chakrabarty D., 2007, ApJ, 654, L73
Gnedin Y. N., Sunyaev R. A., 1973, A&A, 25, 233
Ivanova N. et al., 2013, A&AR, 21, 59
King A. R., 2004, MNRAS, 347, L18
King A. R., 2009, MNRAS, 393, L41
King A. R., Ritter H., 1999, MNRAS, 309, 253
King A. R., Taam R. E., Begelman M. C., 2000, ApJ, 530, L25
King A. R., Davies M. B., Ward M. J., Fabbiano G., Elvis M., 2001, ApJ, 552, L109
Klus H., Ho W. C. G., Coe M. J., Corbet R. H. D., Townsend L. J., 2014, MNRAS, 437, 3863
Kluźniak W., Rappaport S., 2007, ApJ, 671, 1990
Kluźniak W., Wagoner R. V., 1985, ApJ, 297, 548
Kluźniak W., Ruderman M., Shaham J., Tavani M., 1988, Nature, 334, 225
Kluźniak W., Czerny M., Ray A., 1992, in van den Heuvel E. P. J., Rappaport S. A., eds, X-Ray Binaries and the Formation of Binary and Millisecond Radio Pulsars. Kluwer, Dordrecht, p. 425
Kluźniak W., Ruderman M., Shaham J., Tavani M., 1988, Nature, 334, 225
Lyutikov M., 2014, preprint (arXiv:1410.8745)
Motch C., Pakull M. W., Soria R., Grise F., Pietrzyński G., 2014, Nature, 514, 198
Pasham D. R., Strohmayer T. E., Mushotzky R. F., 2014, Nature, 513, 74
Pringle J. E., Rees M. J., 1972, A&A, 21, 1
Rappaport S., Joss P. C., 1977, Nature, 266, 123
Reig P., 2011, Ap&SS, 332, 1
Roberts T. P., 2007, Ap&SS, 311, 203
Sadowski A., Narayan R., Tchekhovskoy A., Abarca D., Zhu Y., McKinney J. C., 2014, MNRAS, 447, 49
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Tauris T. M., Langer N., Kramer M., 2011, MNRAS, 416, 213
Thorne K. S., Ipser J. R., 1968, ApJ, 152, L71
Urbanec M., Miller J. C., Stuchlík Z., 2013, MNRAS, 433, 1903
van Paradijs J., McClintock J. E., 1995, in Lewin W. H. G., van Paradjis J., van den Heuvel E. P. J., eds, X-ray Binaries. Cambridge Univ. Press, Cambridge, p. 58
Wagoner R. V., 1984, ApJ, 278, 345
Webbink R. F., 1977, ApJ, 211, 486
Wijnands R., van der Klis M., 1998, Nature, 394, 344
Ziolkowski J., 1985, Acta Astron., 35, 185