An ultraluminous nascent millisecond pulsar

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ABSTRACT

If the ultraluminous source (ULX) M82 X-2 sustains its measured spin-up value of \(\dot{\nu} = 10^{-10} \text{s}^{-2}\), it will become a millisecond pulsar in less than \(10^5\) years. The observed (isotropic) luminosity of \(10^{40}\) erg/s also supports the notion that the neutron star will spin up to a millisecond period upon accreting about \(0.1 \, M_\odot\) — 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 (HMXBs) — 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: Relativistic stars: pulsars, ultraluminous sources, gravitational waves, black holes, accretion

1 A PULSAR IN AN ULTRALUMINOUS SOURCE

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 ULXs and the evolutionary paths of pulsars.

ULXs were universally considered to be accreting black holes, most likely \(\sim 10 M_\odot\) ones in a binary with a high-mass companion, with some sources possibly harbouring “intermediate mass” \(< 10^{3-4} M_\odot\) 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 HMXBs [King 2004], so \(\sim 10 M_\odot\) 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; Reid 2011), and semi-detached systems (accretion powered X-ray pulsars; van Paradijs and McClintock 1995).

Bachetti et al. [2014] report a \(P = 1.37\) s pulsar in M82 X-2, which is spinning up at the rate \(\dot{P} = -2 \cdot 10^{-10}\), and whose emission shows a 2.5 d sinusoidal modulation, interpreted as the orbital motion of the X-ray source revolving around a \(> 5 M_\odot\) 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 a \(\sim 400 M_\odot\) black hole (Pasham et al. 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 J09555116940.8 to be a run-of-the-mill accretion-powered neutron star pulsar endowed with a \(10^{12} G\) magnetic field (dipole moment \(\mu = 10^{30} G \cdot \text{cm}^3\)). 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 \((\dot{L}_X \approx 10^{30} \text{erg/s})\) 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 \(\sim 10^9 - 10^9\) 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 origi-
nate 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 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, \( \dot{\nu} = -P/P^2 = 10^{-10} \, s^{-2} \), the ultraluminous pulsar would become a millisecond pulsar in less than 100,000 years: \( \nu = T \dot{\nu} = 300 \, Hz \) in \( T = 10^5 \, y \). 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 “redback” progenitor), or it could end as a black hole binary, possibly a ULX, upon accretion induced collapse of the neutron star.

2 SPIN-UP 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 a \( \sim 1.4 \, M_\odot \) mass and an apparent (isotropic) luminosity a hundred times the Eddington value, \( L_\times \approx 10^5 \, L_{Edd} \). 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 \( \dot{\nu} = 10^{-10} \, s^{-2} \) is orders of magnitude higher than the values measured in the usual accretion powered X-ray pulsars, e.g., \( 3.7 \times 10^{-13} \, s^{-2} \) in Her X-1, or \( 7 \times 10^{-12} \, s^{-2} \) in Cen X-3 (Bildsten et al. 1997). On the other hand, the spin-up to luminosity ratio \( 10^{-50} \, (\text{erg} \cdot \text{s})^{-1} \) is an order of magnitude lower than the typical ratio observed in the X-ray pulsars.

It is this ratio, \( \dot{\nu}/L_\times = 10^{-50} \, (\text{erg} \cdot \text{s})^{-1} \), 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 is very luminous in hard X-rays, but relatively little mass were accreted onto the neutron star (so that the torque be low). One difficulty with such a scenario is purely empirical: the effective temperature of such a disc, \( T \approx [L_\times/\sigma \pi r_\times^2]^{1/4} \) should be one third the value of 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 \( r_\times = 2 \cdot 10^6 \, \text{cm} \), one would have to have a model in which the mass accretion rate \( \dot{M} \) through the disc terminating at \( \sim 100 \, \text{stel-} \)

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\footnote{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, \( \dot{M}_\times \) would have to be much higher than \( 10^{-4} \, M_\odot/\text{y} \). 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).}
strong magnetic field in the spin-up behaviour of the M82 X-1 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 $r \gtrsim 100 R_0$ for $B \gtrsim 10^{12}$ G), the mass accretion rate would have been lower by a factor $\sim \sqrt{r_{\text{ms}}/r} < 0.1$ 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 the previous section, 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 $\sim \sqrt{r/r_{\text{ms}}} > 10$, 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-1 pulsar. The period alone, $P = 1.37$ s rules out white dwarfs and less compact stars (Thorne & Ipser 1968), and $\sim 10^8$ yr for test particles in the marginally stable orbit is recovered with $r = r_{\text{ms}}$ and $f_2(r) = \sqrt{2}$. The moment of inertia of the neutron star can be written as

$$I = \beta M R^2,$$

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

$$\tau = 2 \pi \dot{v} I,$$

we obtain

$$MR = \frac{f_2(r)}{\beta f_1(R)} \frac{bL_X}{2 \pi \nu} \sqrt{\frac{r c^2}{GM}}.$$  

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

$$\frac{b^2 r}{r_{\text{ms}}} \approx 0.4 \left( \frac{R}{R_0} \right)^2 \left( \frac{\dot{\nu} \times 10^{50} \text{ erg s}^{-1}}{L_X} \right)^2 \left( \frac{M}{1.4 M_\odot} \right)^2.$$  

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

$$\frac{r r_{\text{ms}}}{H^2} \approx \left( \frac{\dot{\nu} \times 10^{50} \text{ erg s}^{-1}}{b L_X} \right)^2 \left( \frac{M}{1.4 M_\odot} \right)^4.$$  

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 co-rotation 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) is $M = 2 M_\odot$, for which all theoretical models give $R < r_{\text{ms}}$. Hence, for standard neutron stars we have an upper limit of $r < 5 r_{\text{ms}}$, corresponding to a corotation frequency of $> 100 \text{ Hz} \times (2 M_\odot/M)$.

Second, a small value of the beaming factor, $b \ll 1$ could in principle allow large values for the inner radius of the accretion disc, $r \sim b^{-2} r_{\text{ms}} \sim b^{-2} R$, 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.

Could the equilibrium period of the pulsar be within an order of magnitude of the present period of 1.37 s, so that in the near future the torque on the neutron star will undergo a reversal of sign owing to magnetic interactions? This would seem to imply that the accretion disc has to terminate close to the co-rotation radius at the current period, at $r \approx r_{\text{co}} = 2 \times 10^6 \text{ cm}$ (Pringle & Rees 1972; Rappaport & Joss 1977; Kluzniak & Rappaport 2007, and references
4.1 An ultraluminous accreting millisecond pulsar

In view of the difficulties associated with the strongly magnetized pulsar model for NuSTAR J09555116940.8, and the coincidences required to make it compatible with the observations, it seems much more natural to assume that \( b \approx 1 \), implying that \( M \approx 1.4 M_\odot \), and that the inner disc radius is comparable to the stellar radius \( r \sim R \approx r_{\text{ms}} \), with no strong upper limits on the future spin frequency of the M82 X-1 neutron star.

The idea that accreting weakly magnetized neutron stars may exhibit pulsations in X-rays is not new, with the discovery of the first eclipsing pulsars we know of systems...
6 CONCLUSIONS

A neutron star in a high mass X-ray binary (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 J09555116+940.8.

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 could in fact turn out to be harmonics of 1.67 Hz, i.e., that source may be a $P = 0.6$ s pulsar.

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