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Millisecond pulsar formation in high-mass X-ray binaries

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The discovery of three coherently pulsing ultra-luminous X-ray sources (ULXs) with short periodicities (~ 1 s), such as NuSTAR J095551+6940.8, suggests that many ULXs harbour neutron stars. Their extremely high spin-up rates suggests a new channel of millisecond pulsar formation, by neutron star spin up in high-mass X-ray binaries.

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1. Introduction

The discovery of coherent 1.37 s pulsations in the M82 X-2 ULX, with the periodicity modulated by orbital motion in the binary system [1], clearly shows that at least some ULXs are ordinary binary systems composed of a massive star and a neutron star, and not, as suggested previously [2], an intermediate-mass black hole.

The ULX in M82 with its pulsar NuSTAR J095551+6940.8, is not a unique source. It has been anticipated [3] that NGC 7793 P13 in particular, as well as other some other ULXs, will also exhibit coherent pulsations, and these were indeed reported in the following year (2016) by two groups [4, 5]. The periodicity of 0.47 s secures the identification of neutron star ULXs, decisively ruling out a white dwarf as the pulsator. The discovery of a third ULX pulsator, NGC5907 ULX1, at a period of 1.13 s rapidly followed [6]. It seems clear that the number of ULX neutron stars must be enormous, the exact fraction of neutron stars among ULXs depending on the beaming degree of emission and on the duty cycle of the pulsing phase [3, 7, 8].

The three sources have apparent (isotropic) luminosities of 2×10^{40}, 5×10^{39}, and 10^{41} erg/s, respectively, so it is likely that they are inherently super-Eddington, otherwise the emission would have to be beamed into a solid angle not exceeding 1% of 4π. If they are not beamed [3], the theory of accretion disks must be extended to allow for mass acretion rates exceeding 100 Eddington luminosities. If they are beamed, which would allow the accretion disk to be locally Eddington luminosity limited and for the disk to be truncated by the magnetospheric radius far from the neutron star [7, 8], then it must be understood why or how the accreting fluid does not release most of its energy at the pole of the neutron star—in this scenario the disc would be truncated at $R_{\rm M}\sim 10-100$ stellar radii (R) for the three sources [8], so a fraction of no more than $R/R_{\rm M}\sim 0.01-0.1$ of the accretion luminosity should be released in the disk.

2. Magnetic dipole

Currently, the estimates of the magnetic dipole of the ULX neutron stars are model dependent and span a range of seven orders of magnitude. Bachetti et al. [1] assume the pulsar is near spin-equilibrium and has an ordinary magnetic field of $\sim 10^{12}$ Gauss (corresponding to a magnetic dipole $\mu\sim10^{30}\,{\rm G\cdot cm^3}$). On the assumption that the local luminosity of the accretion disk at the magnetospheric radius has the Eddington value, magnetic dipoles of $\mu\sim10^{28}\,{\rm G\cdot cm^3}$, $\mu\sim10^{29}\,{\rm G\cdot cm^3}$, and $\mu\sim10^{31}\,{\rm G\cdot cm^3}$ have been obtained for NGC 7793 P13, M82 ULX2, and NGC5907 ULX1, respectively [8]. Several authors [9, 10, 11] assume that the pulsar is a magnetar ($\mu\sim10^{33}\,{\rm G\cdot cm^3}$), which would have the advantage that its high luminosity would not require supercritical luminosities from the surface, one of the photon polarizations being subject to an electron opacity much lower than Thomson—however, super-Eddington luminosities from a magnetically confined accretion column can be obtained in ordinary X-ray pulsars [13]. Still another possibility is suggested by the unusually low ratio of the spin-up to the luminosity of NuSTAR J095551+6940.8, which is consistent with the low torques that are present when the inner radius of the accretion disk is comparable with the neutron star radius or its marginally stable orbit, the ISCO, which would imply $\mu\sim10^{26}\,{\rm G\cdot cm^3}$ [3].

3. Rapid spin-up

The rate of change of the period is directly measured and corresponds to a spin-up rate of $\dot{\nu} = 4 \times 10^{-11}$ for P13, $\dot{\nu} = 1 \times 10^{-10}$ for M82 ULX2, and $\dot{\nu}$ =several$\times 10^{-9}$ for NGC5907 ULX1 (the instantaneous rate has not been measured for this source). Of the sources under discussion, NGC5907 ULX1 is an extreme case, it seems to have the highest theoretically possible spin-up rate for a neutron star in a high-mass X-ray binary.

If the magnetic dipole is indeed on the order of $\mu \sim 10^{26}\,\mathrm{G{\cdot}cm^3}$, as argued in ref. [3] for M82 ULX2, nothing can stop the neutron star from spinning up to millisecond periods. The expected lifetime of the high-accretion phase of the high-mass X-ray binary undergoing unstable mass transfer is on the order of $T = 10^5$ years [12], and in that time, at a rate of $\dot{\nu} = 1 \times 10^{-10}$ the neutron star would spin up to a frequency of [3] $\nu = T\dot{\nu} = 300\,\mathrm{Hz}$, i.e., a period of about 3 ms. If the magnetic dipole is higher, than the neutron star would reach spin equilibrium before becoming a millisecond pulsar, but could still be spun up to several dozen milliseconds [8], a period comparable to that of young post-supernova explosion pulsars, such as the Crab.

4. Eternal youth

There is a caveat that must be mentioned. It is most curious that all three of the ULX pulsars have a fairly long period of $\sim$ 1 s. At such high spin up-rates they would have been spun up to the current periods in a few hundred years, but it seems unlikely that we are observing systems that young. On the other hand, if the systems are close to spin-equilibrium and are undergoing alternate phases of spin-up and spin-down, as ordinary X-ray pulsars do, why are all three systems in the spin-up phase? Further, in the spin-down phase, according to the current models, the torques are expected to be much lower than in spin-up, c.f. [14] and references therein, so the spin-up phase should be much shorter than the spin-down. Is some kind of a selection effect involved?

It has been suggested that the neutron star magnetic dipole decreases with the amount of mass accreted [15, 16]. If true, the ULX pulsars would have had a higher magnetic field initially, hence a larger magnetospheric radius with correspondingly longer equilibrium periods, and lower accretion disk luminosities ($\propto GM/R_{\mathrm{M}}$), and possibly lower accretion rates onto the surface. This could offer a resolution of the puzzle of apparent youth of the systems. Further, as time goes on and the magnetic dipole decreases even more, it is possible that the pulsations disappear, just as they do in the ordinary millisecond accreting pulsars.

5. Millisecond pulasrs in ULXs

Future observations of the discussed sources will reveal whether the spin-up is a persistent feature of these particular systems, or to the contrary, whether they begin to spin down after some years or decades, as the ordinary X-ray pulsars do. However, it is already clear that there exist high-mass X-ray binaries containing neutron stars subject to extremely high accretion spin-up torques, as well as that there must be numerous neutron star ULX systems.

Given the range of observed magnetic dipoles in the general pulsar population, it is virtually certain that some ULXs contain weakly magnetized neutron stars. The older systems among these, in which $\sim 0.1 M_{\odot}$ has been transferred, will contain a millisecond pulsar.

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