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**Initial parameters of neutron stars**

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**Abstract.** A subpopulation of neutron stars (NSs), known as central compact objects (CCOs) in supernova remnants, are suspected to be low-field objects basing on \(P - \dot{P}\) measurements for three of them. The birth rate of low-field NSs is probably comparable with the birth rate of normal radio pulsars. However, among compact objects in High-Mass X-ray Binaries (HMXBs) we do not see robust candidates for low-field NSs. We propose that this contradiction can be solved if magnetic fields of CCOs was buried due to strong fall-back, and then the field emerges on the time scale \(10^4 - 10^5\) yrs.

Our talk presented during the conference consisted of two parts. In the first we presented results on estimates of initial spin periods of neutron stars (NSs) associated with supernova remnants (SNRs). These results are published already (Popov & Turolla 2012), so in this contribution to the conference proceeding we concentrate on the second part of the talk related to a possible evolution of one of subpopulations of isolated NSs.

Among young isolated NSs a very special group of objects is recognized. They appear as central compact objects (CCOs) in SNRs, and some of them are dubbed “an antimagnetars” (Halpern & Gotthelf 2010). For these sources (three cases up to now) periods about \(P \sim 0.1-0.5\) s are measured, together with period derivatives \(\dot{P} \sim 10^{-17}\) s/s. This allows to obtain an estimate of the magnetic field \(B \sim 10^{10} - 10^{11}\) G. It is suspected that all CCOs belong to the class of antimagnetars, and we accept this hypothesis below.

More than 20 radiopulsars (PSRs) have robust associations with SNRs. Average age of such systems is above \(10^4\) yrs. On the other hand, there are about 8 CCOs, and their ages are below \(10^4\) yrs, on average. Estimates show that the birthrate of antimagnetars is comparable with the birth rate of PSRs (even taking into account beaming for PSRs). Below we assume that about \(1/3\) of newborn NSs are antimagnetars.

Starting with these assumptions we can ask: what is the fate of antimagnetars? One possibility is that they just cool down and become invisible as bright thermal X-ray sources. Still, having \(1/3\) of NSs born with low magnetic fields we can look at young X-ray binaries to investigate further fate of such objects, assuming that the fraction of low-field NSs is the same for isolated objects and (at least) for the first-born NSs in binaries. Let us discuss the population of high-mass X-ray binaries (HMXBs). These systems are young, because the second massive companion is (usually) still on the main sequence. The majority of HMXBs belong to the class of Be/X-ray binaries. Several other systems have wind-fed accretion. This allows us to assume that total accreted mass is not large enough to influence significantly the magnetic field of a compact object, as it happened in millisecond PSRs.
A NS in a binary with $P_{\text{orb}} \sim 10$ days with $B \sim 10^{10}$ G and accretion rate $\dot{M} \sim 10^{15}$ g/s is expected to have $P \lesssim 0.1$ s. This is valid for any regime of accretion: standard disc, standard wind, or the new model proposed by [Shakura et al. (2012)]:

\[ P_{\text{wind}} = 4.4(P_{\text{orb}}/10 \text{ d})^{1/2} \mu_{30}^{-1/2} M_{16}^{-1/2} (v/300 \text{ kms}^{-1})^{2} \text{ s.} \]  

(1)

\[ P_{\text{disc}} = 5.47\mu_{30}^{6/7} M_{16}^{-3/7} \text{ s.} \]  

(2)

\[ P_{\text{Shak}} = 8.18\mu_{30}^{12/11}(P_{\text{orb}}/10 \text{ d}) M_{16}^{-4/11} (v/300 \text{ kms}^{-1})^{4} \text{ s.} \]  

(3)

In catalogues of Be/X-ray binaries [Raguzova & Popov 2005; Reig 2011] there are very few systems, in which NSs can have low magnetic fields. In the study by Chashkina & Popov (2012) it was shown that in a large (40 objects) sample of Be/X-ray binaries in SMC there are no NSs with fields below $10^{11}$ G. Note, that many different methods to derive field estimates have been used.

At this point we see a contradiction. About 1/3 of NSs in not-very-wide HMXBs are expected to have periods below $\sim 0.1$ s, which corresponds to low magnetic field, but very few such objects are observed. Discussion of this contradiction is the central point of this note.

Older CCOs are not known also among sources selected by their thermal emission. Among close-by cooling NSs only normal pulsars and so-called Magnificent seven sources are known [Popov 2011]. However, even if CCOs follow slightly different cooling curves due to accreted low-element envelopes [Yakovlev & Pethick 2004] they have to be bright at least for $10^5$ yrs, then older (than known CCOs) bright X-ray sources in SNR (or without them) with CCO-like properties are expected. There is some evidence that the source 2XMM J104608.7-594306 can be a low-magnetized NS (Mancini Pires et al. 2012, see also these proceedings), but in this case the situation is not certain, yet, and there is a possibility that spin period is short. Population synthesis of close-by NSs does not require additional contribution from low-field NSs [Popov et al. 2010]. According to this study the global NS formation rate is consistent with a single-mode field distribution, in which there is no room for a large fraction of NSs with typical fields below $10^{11}$ G. A detailed discussion of formation rates of NSs of different types was given by Keane & Kramer (2008). However, these authors did not discuss CCOs (i.e., low-field NSs). Still, inclusion of such objects will only strengthen their conclusion that there should be evolutionary links between different subpopulations of isolated NSs.

A possible solution can be related to emerging magnetic field in CCOs. If after a strong fall-back episode NS’s magnetic field was buried by a thick layer of matter, then we can observe a young hot NSs with low magnetic field [Ho 2011; Viganò & Pons 2012]. Having $\geq 100$ HMXBs with typical lifetime $\sim 10^7$ yrs, we expect that the youngest of them should have ages $\sim 10^5$ yrs. Then, field should emerge on the timescale few $10^4 - 10^5$ yrs.

Now we have to look at normal PSRs. Emerging field effectively means that there is “injection” of PSRs with $P \sim 0.1-0.5$ s and normal magnetic field (on average,}

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1http://xray.sai.msu.ru/raguzova/BeXcat/
field can be slightly lower than the standard value due to field decay, Ho 2011). Surprisingly, this is what was discussed in many papers [Vivekanand & Narayan 1981; Narayan & Ostriker 1990] starting from early 80s. Later on, with new data these results were reconsidered.

Still, Vranić & et al. (2004) conclude that \( \sim 40\% \) of pulsars can be born with periods 0.1-0.5 s. In a recent study (Popov & Turolla 2012) we show that a significant fraction of NSs can have such periods. Among normal PSRs in SNRs this fraction (however, on low statistics) is below 40\%. Then, there is a room for pulsar “injection” which can solve the problem of absence of low-field NSs in HMXBs.

Some contribution to PSRs with field \( 10^{10} - 10^{11} \) G and periods about few tens of second can be related to disrupted binaries in which NSs have been mildly recycled (Belczynski et al. 2010). PSRs with long periods (for a given field and age) can appear due to fossil discs (Yan et al. 2012).

In a recent paper Vranić & Melrose (2011) demonstrated that the approach based on “pulsar current” studies is very model dependent. Then, results obtained by this methods should be taken with care. We conclude, that the question of existence of pulsar “injection” with normal fields and \( P \sim 0.1-0.5 \) s is uncertain, but such a possibility due to emerging magnetic field on a time scale \( \sim 10^5 \) yrs can solve the mystery of absence of significant number of low-field NSs in HMXBs.

On \( P - \dot{P} \) diagram emerged PSRs might appear at \( P \sim 0.1-0.5 \) s and field slightly below the standard one. Such PSR are expected to have negative braking indices, as their field is growing. About 20-40 objects with such properties are known. Growing magnetic field was also proposed for a young PSR J1734-3333 (Espinoza et al. 2011). However, this is a PSR with \( P = 1.2 \) s and large magnetic field, i.e. different from what we expect for mature (emerged as PSRs) CCO-like NSs (see, however, Vigano & Pons 2012).

Normal PSRs with detected thermal emission which does not fit well their characteristic ages (too hot for a given age) can be former CCOs. In this case their present day characteristic ages are not representative, and they are still young to have high temperatures. On other hand, NSs with buried (and then emerged) field should not be necessarily hot, because their masses can be high enough to start rapid cooling due to direct URCA processes. Then a NS becomes visible only after field emergence on the PSR stage.

The only Be/X-ray binaries with very short periods are A 0538-66 and SAX J0635+0533. A0538-66 demonstrates episodes of very high luminosity. Magnetic field for the NS is estimated as \( \sim 10^{11} \) G. The situation with SAX J0635+0533 is more interesting as it has low luminosity (Cusumano et al. 2000). Before the paper by Shakura et al. (2012) appeared estimates of the magnetic field have produced very low values. Using eq. (2) or eq. (3) and standard assumptions we obtain field \( \lesssim 10^{10} \) G for SAX J0635+0533. Potentially, it can be an aged CCO-like NS with yet-non-emerged field. This can point to the young age of a NS in this system.

X-ray pulsations can be hardly detectable if the spin axis is nearly parallel to the magnetic dipole axis. This is a possibility for low-field NSs to avoid identification via period measurements in accreting systems, and so can be an alternative to field emergence. Note, that in the case of CCOs only in few cases periods are detected. This,

\[ \text{The source SMC X-1 with } P = 0.71 \text{ s is also a bright object, and the field is estimated to be normal: } \sim 10^{12} \text{ G.} \]
potentially, also can be linked to small angles between spin and magnetic axis. Among Be/X-ray binaries there is a significant number – roughly one third – of sources with undetected periods (Raguzova & Popov 2005). However, those objects without spin period detection are mostly not well studied sources. In addition, some of them can be WD binaries (like, most probably, γ Cas, see Lopes de Oliveira et al. 2006). Significant alignment of spin and magnetic axis for low-field sources on a time scale below one million years is not expected in models of pulsar evolution, so we neglect this possibility here. Note, that for HMXBs there is no evidence for alignment or counter-alignment even for stronger magnetic fields (Annala & Poutanen 2010). Then significant evolutionary alignment for low-field objects seems to be not probable.

Another option can be related to smaller amplitude of pulsating signal for low magnetic fields. However, for not too high accretion rates in the case of well-studied sources pulsations must be detectable even for low fields.

There is also an important possibility that in close binaries with one episode of strong mass exchange (all Be/X-ray binaries belong to this class) fall-back is very small (Pejcha et al. 2012). Potentially, this can result in smaller fraction of low-field NSs in binaries. However note, that to screen the field it is enough to have just a small fall-back ≪ 0.1 M⊙ (Ho 2011; Viganò & Pons 2012). Anyway, this option has to be studied in more details.

We conclude that emerging magnetic field on the time scale ∼ 10⁴ – 10⁵ yrs in CCO-like objects is the best possibility to explain the whole set of data.

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