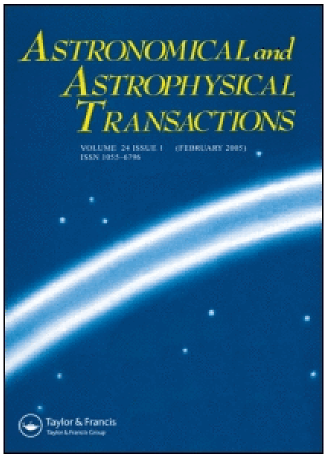

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EVOLUTION OF ISOLATED NEUTRON STARS IN GLOBULAR CLUSTERS: NUMBER OF ACCRETORS

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With a simple model from the point of view of population synthesis we try to verify an interesting suggestion made by Pfahl and Rappaport (2001) that dim sources in globular clusters (GCs) can be isolated accreting neutron stars (NSs). Simple estimates show, that we can expect about 0.5–1 accreting isolated NS per typical GC with $M = 10^5\,M_{\odot}$ in correspondence with observations. Properties of old accreting isolated NSs in GCs are briefly discussed. We suggest that accreting NSs in GCs experienced significant magnetic field decay.

Keywords: Neutron stars; Globular clusters; Accretion

1 INTRODUCTION

There are expected to be as many as 10^8–10^9 Galactic isolated neutron stars (NSs) a non-negligible fraction of the total stellar content of the Galaxy. In the last 10 years they have received special attention. The idea of observing such objects in the X-ray range has emerged soon after discovery of the first X-ray sources (Ostriker *et al.*, 1970). Now we are sure that a few dim ROSAT sources are nearby isolated neutron stars (see Neuhäuser, 2001; Walter, 2001).

All these sources emit a thermal spectrum at $\approx$100 eV and the derived column densities place them at relatively close distances ($\leq$150 pc) with luminosities $L \sim 10^{30}$–10^{31} erg s^{-1}. Several of them can be visible due to accretion from the interstellar medium (ISM), others due to thermal emission of cooling relatively young, $\sim$1 Myr, NSs (see Treves *et al.*, 2000 for a recent review of accreting isolated NSs, and Popov *et al.*, 2000b for discussion on relative fraction of cooling and accreting NSs in the solar vicinity).

X-ray observations of globular clusters (GCs) show a large population, $>$30, of dim X-ray sources (hereafter dim GC sources) with $L \sim 10^{31}$–10^{34} erg s^{-1} (Verbunt, 2001). Pfahl and Rappaport (2001) suggested that part of dim GC sources can be old isolated accreting NSs. In this short note we try to analyze this idea from the point of view of population synthesis (see Lipunov *et al.*, 1996 for detailed description of population synthesis method).

Population synthesis of isolated NSs in the Galactic disk was made previously by several authors (see Popov *et al.*, 2000a,b). Evolution of isolated NSs in the Galactic disk and in GCs

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must be significantly different. Here we try to explore this with a simple model evolution of progenitors of isolated accreting NSs in GCs. In the next section we briefly discuss our models. In Section 3 we present our results, and in the last section we discuss properties of old accreting NSs in GCs.

2 THE MODEL

An isolated NS can pass through four main stages of evolution: Ejector, Propeller, Accretor and Georotator (see Lipunov, 1992 for detailed description of each stage). We consider, that all NSs are born as Ejectors and then while they slow down (and/or their magnetic field decays) they pass though the Propeller and Accretor stages. If spatial velocity and/or magnetic field of a NS are very high, then this NS can appear as a Georotator after the end of the stage of ejection.

For constant magnetic field we can estimate the period of time which a NS spends on the stage of Ejector, t_E, as (see for example Popov and Prokhorov, 2000)

$$t_E \sim 10^9\,\mathrm{yrs}\,\mu_{30}^{-1} n^{-1/2} v_{10}, \tag{1}$$

where $\mu_{30} = \mu/10^{30}\,\mathrm{G\,cm^3}$ – magnetic moment, $v_{10} = v/10\,\mathrm{km\,s^{-1}}$ – velocity relative to ISM, n – ISM number density.

For the Propeller stage one can find in the literature a lot of spin-down regimes, but in the case of constant magnetic field the Propeller stage is always considered to be much shorter than the Ejector stage (see Lipunov and Popov, 1995). Taking this into account we neglect the time spent by NSs on the Propeller stage in our simple estimates (for field decay this stage becomes very important, see Livio *et al.*, 1998; Colpi *et al.*, 1998; Popov *et al.*, 2000a).

We calculate relative fraction of Accretors (*i.e.* objects with $t_E < t_{\mathrm{Hubble}} = 10^{10}$ yrs which cannot appear as Georotators due to relatively low magnetic field or/and spatial velocity) among other isolated NSs for typical disk and GC conditions after 10^{10} yrs of evolution. In the case of the Galactic disk we use constant starformation rate, and in the case of GC starformation rate is considered as a δ-function (*i.e.* a starformation burst at $t = 0$).

For both cases we use Maxwellian velocity distribution with $\sigma = 140\,\mathrm{km\,s^{-1}}$, and log-normal distribution for magnetic fields of NSs typical for radiopulsars (see Popov *et al.*, 2000a,b for discussion of these choices). For GC, velocity was truncated at $30\,\mathrm{km\,s^{-1}}$, which is a typical escaping velocity from the cluster. For the Galactic disk we use typical value of ISM number density $n = 1\,\mathrm{cm^{-3}}$, for GCs – $n = 100\,\mathrm{cm^{-3}}$ (see Pfahl and Rappaport, 2001 and short discussion below). In our simple model n, μ, and v are considered to be constant during the whole evolution.

For both populations (disk and GCs NSs) we assume the same parameters of NSs (initial spin periods, moments of inertia, masses etc.). Initial spin periods are assumed to be equal to 0.020 sec for all NSs in our calculations. Our previous estimates (Popov *et al.*, 2000a) show that small variations of this parameter do not change final results for Accretors.

3 CALCULATIONS AND RESULTS

Our aim is to calculate the number of accreting isolated NSs per typical GC with the total mass $10^5\,M_\odot$ (we neglect the fact the GC mass slightly decreases during GC evolution).

As the first step we compare fractions of Accretors in GCs and in the Galactic disk. To do it we just run our simple models (described in the previous section) for the same numbers of NSs for each case. An important result is the following: for GCs, fraction of Accretors relative to other stages is about 26 times lower than in the Galactic disk. Of course it is just a rough estimate, but it shows, that even for high ISM density ($n = 100\,\mathrm{cm}^{-3}$) due to escaping of the most part of population of isolated NSs number of isolated accreting NSs in GCs is small. Escaped NSs are considered as Ejectors as far as they have high spatial velocities and move in low-density surrounding. One can compare typical escaping velocity, $30\,\mathrm{km\,s}^{-1}$, with typical velocity of Accretors in the Galactic disk (Popov *et al.*, 2000b), $>50\,\mathrm{km\,s}^{-1}$.

Then we try to estimate the number of Accretors for a typical GC. In the Galactic disk Accretors form about 1% of the total NS population (Popov *et al.*, 2000a). The mass of the disk population of stars is about $7 \times 10^{10}\,M_{\odot}$. Typical mass of a GC is assumed to be $10^5\,M_{\odot}$. We note, that for the Galactic disk fraction of 1% was calculated for constant star-formation rate (Popov *et al.*, 2000a) for GCs we calculate it for a startformation burst (age of the burst is equal to the age of the disk).

In the disk we expect about $N = 10^9$ isolated NS. *i.e.* about 10^7 Accretors. After simple calculations we obtain about $(10^9 \times 0.01 \times 10^5)/(26 \times 7 \times 10^{10}) \approx 0.55$ Accretors per typical GC ($M = 10^5\,M_{\odot}$). If total number of NSs in the disk is lower, then our estimate should be lower too.

We can also calculate the number of Accretors per GC in a more simple way. Let us take the Salpeter mass function, and assume, that NSs are born from mass interval 10–40 solar masses (Lipunov *et al.*, 1996). In a simple model described above (startformation burst, 10^{10} years of evolution, constant parameters of the ISM and NSs during their evolution) we can calculate that about 0.25% NSs become Accretors in GCs (mainly because most part of NSs leave GCs due to high kick velocity, but nearly all NSs which stay bounded with the GC become Accretors). It gives us about 1.1 Accretor per GC. It can be considered as an upper limit on the number of Accretors, as far as for GCs the number of massive stars can be lower (initially) then it follows from the Salpeter mass function, and evolution of NSs can proceed with an average ISM density lower than the value $n = 100\,\mathrm{cm}^{-3}$ which we used in our calculations: all these factors decrease the number of Accretors.

So, we can roughly estimate the number of Accretors per GC with the total mass 10^5 solar masses as 0.5–1. We also note, that coincidence of the two estimates can be considered as an additional (but not very strong) argument for the number of Galactic NSs equal to 10^9.

To summarize, simple evolutionary estimates do not contradict the idea, that at least part of dim X-ray sources in GCs can be old accreting isolated NSs. It is important to repeat such calculations in more details (spin evolution, dynamical evolution, realistic ISM distribution etc.) and with realistic models of field decay.

4 DISCUSSION

It is reasonable to discuss in brief the following important topics:

1. Interstellar gas density in GCs.
2. Observed temperatures of dim sources in GCs.
3. Periods of accreting NSs in GCs (no pulsations were detected from dim GC sources) and rotational equilibrium (period changes).
4. Magnetic field distribution for Accretors in GCs.

Pfahl and Rappaport in their paper suggested and used high value of the gas number density in GCs: $100\,\mathrm{cm}^{-3}$. We used the same value in our calculations. Actually, nobody has observed gas in GCs at such high density. But it is reasonable to expect these high values and observations provide high upper limits: $\sim$(50–100) cm^{-3} (Knapp *et al.*, 1996).

Average density along the track during a NS evolution can be lower than the high value we used. This effect will increase the duration of the Ejector stage (see Eq. 1), and correspondently decrease the number of Accretors. But if we *a priory* consider dim X-ray sources to be Accretors, we have to take high number density in order to explain observed luminosities (Pfahl and Rappaport, 2001). The same high density comes from estimates of gas accumulation in GCs due to mass loss from stars (Knapp *et al.*, 1996; Pfahl and Rappaport, 2001).

That's why we argue that the effect of decreasing of the number of Accretors is not very significant. Otherwise, in the case of low density the hypothesis of accreting isolated NSs should be rejected due to difficulties with the explanation of X-ray luminosity of the sources under discussion.

Relatively high temperatures of dim GC sources (0.1–0.5 keV), which is higher than for dim ROSAT INS candidates (<200 eV, with typical values 50–100 eV, see Treves *et al.*, 2000; Walter, 2001; Neuhäuser, 2001) are in favour of the accreting hypothesis (both for single and binary NSs). For example, young cooling NSs, age $\sim$1 Myr, should be cooler than Accretors in the case of polar cap accretion. In Popov *et al.* (2000b) the authors plot temperature distribution for Accretors (without magnetic field decay) for the disk population. The maximum of the distribution corresponds to $\sim$400–500 eV, the total range is about 100–1000 eV (depending on the magnetic field and accretion rate). But as far as luminosities of dim GC sources are higher than luminosities of the disk accreting sources (the ISM density is higher), they should be also slightly warmery. It may be accretion in that sources proceeds onto very large polar cap due to magnetic field decay (objects are very old).

Old Accretors in the disk should have relatively long periods if their magnetic field does not decay significantly (Lipunov and Popov, 1995). But in GCs spin periods for the same magnetic field should be much shorter, as far as the ISM density is higher:

$$p_A \sim 42\mu_{30}^{6/7} v_{10}^{9/7} n_{100}^{-3/7}\,\mathrm{s}. \tag{2}$$

Here, p_A is a critical period for transition from the stage of Propeller to the stage of accretion (Lipunov, 1992). On that stage a NS continues to spin down till it comes to rough equilibrium with turbulized ISM. So, typical periods should be close to some value,

$$p_{\mathrm{turb}} \sim (100\text{–}300) v_{10}^{13/3} n_{100}^{-2/3} \mu_{30}^{2/3}\,\mathrm{s}, \tag{3}$$

for $n = 100\,\mathrm{cm}^{-3}$ (Lipunov and Popov, 1995; Konenkov and Popov, 1997), slightly longer than p_A. The realistic period distribution for accreting isolated NSs will be presented elsewhere (Prokhorov, Popov and Khoperskov, 2002). It is characterized by broad maximum near p_{turb}, slightly shifted to longer periods.

In the picture described above spin periods of isolated accreting NSs in GCs can be observed, and lack of period detection is not in favour of Pfahl and Rappaport (2001) hypothesis. To solve this problem it is necessary to introduce something non-standard for NSs in GCs. For example significant field decay, so that Alfven radius will be about the size of a NS, and no pulsations can be observed in that case due to low level of modulation. As we note above, it can also explain relation between temperature and luminosity of that sources (due to large polar cap area).

Periods and their derivatives (if detected) should show significant fluctuations on the time scale $R_G/v \sim v^{-3} \approx 5.9\,\mathrm{yrs}\,v_{10}^{-3}$. On the same time scale one expects variations of luminosity, and they are observed (Pfahl and Rappaport, 2001) on the time scale ~1 year. Detection of spin periods and analysis of their correlation with luminosity changes are very desirable.

Magnetic fields of Accretors in GCs should be, on average, smaller than in the disk, because it is much easier to become Accretor in a GC (density is higher, and typical spatial velocity is lower: in disk it is about $50\,\mathrm{km\,s^{-1}}$, and in GCs about $20\,\mathrm{km\,s^{-1}}$). For lower magnetic fields it is more difficult to reach p_A (see Eq. 2), so there should be low values of the magnetic field for which only in high density environment of GC it is possible for a NS to become an Accretor.

We also note, that field decay can both decrease and increase number of Accretors (Colpi *et al.*, 1998; Livio *et al.*, 1998; Popov *et al.*, 2000a; Popov and Prokhorov, 2000). So, significant field decay, which make it easier for a NS to reach the stage of accretion, can compensate the effect of lower average ISM density along the evolutionary path of the NS.

In principle some of dim GC sources can also be Georotators accreting warm ISM (aka MAGACs, see Rutledge, 2001). These objects should be relatively hard sources, without any periodicity on the timescale $<10^5$ s. But for GC conditions very large magnetic moments are required to become a Georotator, because in dense ISM ($n \sim 100\,\mathrm{cm^{-3}}$) among low velocity isolated NSs, which can stay in the GC, only most magnetized objects can become Georotators instead of becoming Propellers (and then Accretors). It makes this hypothesis unlikely. If one tries to explain dim GC sources as young cooling NSs, then it is necessary to accept, that they are really very young to be so hot and luminous. It is difficult to explain why in several GCs young NSs are observed (Andrei Zakharov noted to us, that there is a possibility of NS formation in GCs due to recent star formation from the accumulated matter, which was lost by cluster members on their late stages of evolution). Most probably dim GC sources are accreting isolated NSs with decayed magnetic fields in correspondence with Pfahl and Rappaport (2001) hypothesis.

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