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Young isolated neutron stars from the Gould Belt

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Abstract. We present Log N – Log S distribution for close young isolated neutron stars. On the basis of Log N – Log S distribution it is shown that seven ROSAT isolated neutron stars if they are young cooling objects are genetically related to the Gould Belt. We predict, that there are about few tens unidentified close young isolated neutron stars in the ROSAT All-Sky Survey.

1. Introduction

Among different types of neutron stars (NSs) there is a small group of seven radioquiet isolated NSs discovered by ROSAT (RINSs) (see a review in Treves et al. 2000, and in Russian in Popov, Prokhorov 2002).

Now it is generally accepted, that at least one of these objects (RX J1856, see the table) is a young cooling isolated NS. We assume that all of them belong to this type and make a population synthesis of close young isolated NSs.

Our paper is motivated by the fact, that averaged parameters of the spatial density of radio pulsars in our Galaxy cannot produce enough *coolers*, i.e. NSs which are young (hot) and close enough to be observed, to explain RINSs (Neuhäuser, Trümper 1999, Popov et al. 2000b).

Previously we briefly discussed connection between RINSs and the Gould Belt (Popov et al. 2002). Here we address this question in more details.

2. Model

Main components of our model are: spatial distribution of NS progenitors, NS formation rate, NS cooling histories and model of interstellar absorbtion (i.e. interstellar medium (ISM) distribution). In addition we calculate dynamical evolution of NSs in the galactic potential. This addition does not have a big influence, as far as time scale of our calculations (cooling time scale) is short in comparison with a time in which a typical NS crosses the region of our calculations, and also all other components of the model are independent on NSs velocities. But taking into account of the dynamical evolution makes our calculations more realistic (for example, NSs in our calculations are not produced in 50-100 pc around the Sun, but they can enter this region if they have corresponding velocities; also dynamical evolution is very important for NSs which are born close to the Sun). Also spatial movements of NSs changes distribution of observed sources on the sky in comparison with progenitor distribution.

In brief our model can be described in the following way: NSs are born in the Galactic plane and in the Gould Belt; at birth they recieve a kick velocity; then we follow the evolution of NSs in the Galactic potential; while a NS moves in the Galaxy we calculate (with some time step) ROSAT count rate basing on cooling curves and assumed model of interstellar absorbtion.

Typically we calculate about a thousand of NS evolutionary tracks in each run of the programm (for the final results we perform larger runs with $\sim 10^4$ tracks) and then normalize our results (real number of young NSs in the region we calculate is expected to be about one thousand, depending on the limiting age, NS formation rate and calculated volume).

An evolutionary track is calculated for specified initial position and initial velocity of a NS. All tracks are used on their whole duration and are applied to NSs of different masses, i.e. for each track we have several different cooling

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histories, the number of which depends on the number of different masses we use in this particular run. So (as in Popov et al. 2000a,b) each track actually represents a population of NSs of different masses continuously born at specified place with specified spatial velocity during the whole period of calculation.

We varied parameters of our model (NS formation rate, NSs mass spectrum, time of calculation, time step, parameters of the spatial distribution), in the following subsections we describe in more details parameters corresponding to the results presented in Sec. 3.

2.1. Spatial distribution

We assume that NSs are born in the Galactic disk and in the Gould Belt. NSs are considered to be born with a constant rate. For NS formation rate we assume an estimate of 30 NSs births in 0.6 kpc vicinity of the Sun per Myr. This estimate comes from direct counting of SN progenitors in the Solar vicinity, it is not dependent on the observed SN rate or on radio pulsar statistics, and corresponds to 2.9 10^{-11} massive progenitors per yr per pc^2 (Tammann et al. 1994) (we assume that 90% of core collapse SNae produce NSs).

Among these 30 NSs per Myr 20 are born in the Gould Belt in correspondence with a rate 20–27 SN per Myr given in (Grenier 2000), and the rest are uniformly distributed in the disk in 0.6 kpc around the Sun. It is in correspondence with (Torra et al. 2000), who estimate that about 2/3 of massive stars inside 0.6 kpc are in the Gould Belt, and the rest — in the Galactic disk. The age of the Gould Belt is estimated (Pöppel 1997) as 30– 70 Myr, so now stars with masses about 10 $M_\odot$ are ending their lives, which gives high relative number of SNae.

To take into account possible contribution of farther NSs at low fluxes (about 0.1 cts s^{-1} and lower) we also calculate NSs born in the Galactic disk at distances > 0.6 kpc (but < 3 kpc) around the Sun. The NS formation rate for this region is assumed to be the same as in the close-by parts of the Galactic disk. In a region of 1 kpc around the Sun it gives (together with the same fixed Gould Belt contribution) the rate of ~ 20 SNae of all types per Myr per kpc^2 in correspondence with existing estimates (Tammann et al. 1994) (we follow that paper assuming the fraction of core collapse SNae to be 85%). Here we underestimate the number of far (> 1 kpc) new born NSs in the direction to the Galactic center, but interstellar absorbtion there (see below) is very high in the Galactic plane, and the impact of such underestimation is not serious.

So, 20 NSs per Myr come from the Gould Belt, and 250 NSs per Myr are uniformly distributed in the Galactic plane with a limiting distance from the Sun 3 kpc. The closest Solar vicinity al low galactic latitudes is known to be under populated by massive stars (Maíz-Apellániz 2001), so we assume, that NSs are not born in the Galactic disk at distances < 100 pc from the Sun.

The Gould Belt is modeled as a disk with 500 pc radius and inclination to the Galactic plane equal to 18°. Center of the disk is situated at 100 pc from the Sun in the Galactic anticenter direction. In the center of the disk there is a hole with a radius 150 pc, where NSs are not born (see Pöppel 1997 for detailed describtion of the Gould Belt, and Torra et al. 2000 for a shorter one).

NS are assumed to be born with kick velocities with maxwellian distribution with an average value ~ 225 km s^{-1}. Varying this parameter does not changes our results significantly, but it is clear, that if average velocity is larger, then we can observe less RINSs.

For calculations of NSs evolution in the Galactic potential we use the same parameters and procedure as in Popov et al. (2000b). The Galactic potential is assumed to be axisymmetric consisting of disk, buldge and halo parts (see Paczynski 1990). The Sun was assumed to be at the Galactic plane at a distance 8.5 kpc from the center of the Galaxy.

2.2. Cooling curves and flux calculation

To calculate cooling of NSs we use the data obtained by Sankt-Petersburg group (see Kaminker et al. 2002, and a review in Yakovlev et al. 1999).

We use cooling curves for NSs of masses from 1.1 $M_\odot$ to 1.8 $M_\odot$ with a step 0.1 $M_\odot$ (see Fig. 1). Curves take into account all processes of neutrino emission. EOS used in Kaminker et al. (2002) was introduced in Prakash et al. (1988). It is *Model I* of Prakash et al. for symmetry energy and compression modulus of saturated nuclear matter, K, is equal to 240 MeV. Maximum NS mass in that model is 1.977 $M_\odot$. Neutron superfluidity in the crust and core is ignored, as far as it does not influenced the final results significantly.

We start flux calculations when a NS has an age 10 000 yrs (Vela – the youngest close-by NS – has an age slightly above this number, also NS formation rate which we use in our calculations corresponds to a NS birth every ~ 10 000 yrs in ~ 1.7 kpc region around the Sun). Calculations for each NS are truncated when its temperature falls down to 100 000 K (it corresponds to an age 4.25 Myrs for the lightest NSs ($M = 1.1\,M_\odot$) and less for more massive stars. Such a cool NS could be detected by ROSAT PSPC from the distance of only 10 pc as a source with count rate $\sim 5\,10^{-3}$ cts s^{-1}.

In our calculations we assume, that NSs have flat distribution in mass spectrum between 1.1 and 1.8 solar masses. With the numbers above (4.25 Myrs and 10 000 yrs) we can say, that each track in our calculation represents $(425 \cdot 8)$ NSs of eight different masses born with a time step 10^4 yrs at the same place with the same initial velocity in a period 4.25-0.01 Myrs ago.

We assume that emission comes from the whole surface of a NS. It is a reasonable assumption as far as pulsed fractions for RINSs are very low or there are only upper

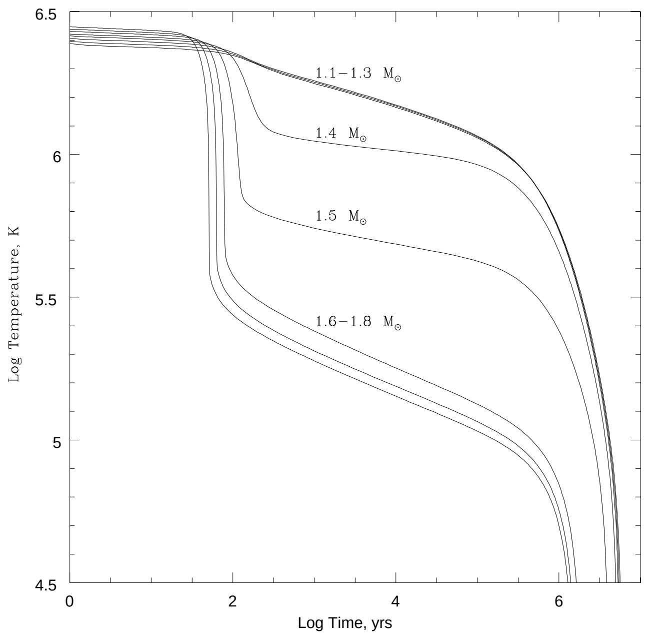

Fig. 1. Cooling curves for different masses (here we use calculations presented in Kaminker et al. 2002). Curves from top to bottom corresponds to masses 1.1; 1.2; ...; 1.8 $M_{\odot}$. On curves and everywhere in the text we refer to the effective surface redshifted (i.e. observed at infinity) temperatures in the case of a pure black body emission (no possible atmospheric effects are included)

limits (see Haberl, Zavlin 2002). We do not take into account any effects of NS's atmosphere.

As one can see from the Fig. 1 the main contribution to Log N - Log S distribution is given by NSs with masses $< 1.5\,M_{\odot}$ (young isolated NSs which are observed in several SN remnants as compact X-ray sources due to their thermal radiation also should be relatively low massive objects, see Kaminker et al. 2002). Observations of binary radio pulsars suggest, that NSs masses are strongly peaked between 1.3 and 1.4 $M_{\odot}$. Such distribution was also tested in our calculations. It does not change our result significantly (numbers of RINSs are increased by ~ 30 %).

2.3. ISM and absorbtion

As far as we expect our NSs to emit most of their luminosity at soft energies $\sim 20 - 200$ eV (which corresponds to temperatures about 10^5–10^6 K) we have to take into account interstellar absorbtion. Absorbtion is a very important feature of our model. Any attempts to estimate the amount of observable cooling isolated NSs using unabsorbed flux *greatly* overestimate this number.

For ISM distribution we use the same model as in Popov, Prokhorov (1998). The Local Bubble is modelled as a sphere with 140 pc radius and ISM number density 0.1 cm^{-3}. Typical column densities, $N_{\rm H}$, for observable RINSs are about 10^{19}–10^{21} cm^2.

After a column density is calculated for a current position of a NSs we calculate unabsorbed flux basing on current temperature, radius of a NS and its distance from the Sun, and apply starndard procedure to calculate ROSAT counts.

Outside the Local Bubble in directions close to the Galactic plane absorbtion starts to play a crucial role. That is why regions closer to the Galactic center (< 7 kpc), where NS formation rate should be higher than in the Galactic disk in the Solar vicinity, cannot add many sources to our sample (at $N_{\rm H}$ =3 10^{21} cm^{-2} even young and hot low mass NSs with $kT \sim 0.1$ keV can not be detected from the distance 1 kpc in the ROSAT Bright Survey (count rate > 0.2 cts s^{-1})).

Our model does not take into account small irregularities of the ISM distribution (except the Local Bubble, but even it we treat in a simplyfied way). They can be important if one makes an attempt to produce a realistic map of RINSs distribution on the celestial sphere. But for the case of calculation of averaged over the sky Log N – Log S distribution our approximation is valid.

3. Results

Our aim is to calculate Log N – Log S distribution for young close isolated NSs born at the Gould Belt and in the Galactic disk, and to compare this distribution with known INSs observed by ROSAT due to their thermal emission.

Main results are presented in the Fig. 2. We present a curve for NSs born in the Gould Belt and the Galactic disk and a curve only for the disk to show the relative importance of the Gould Belt. All curves are refering for the whole sky.

We put observed points basing on ROSAT data for the "magnificent seventh" (seven RINSs) and six other close-by young isolated NSs. Note, that for the later we use *total* count rate, where non-thermal component can be significant, it is especially important for the Vela pulsar and for 1929+10.

It was shown before (Neuhäuser, Trümper 1999, Popov et al. 2000b) that cooling NSs with spatial density of normal radiopulsars cannot explain the observed Log N – Log S distribution for RINSs. In Popov et al. (2002) we suggested, that the Gould Belt is responsible for that increased spatial density of young NSs, Here we show by population synthesis calculations, that increase in density is easily explained by the local feature — the Gould Belt, and the curve excellently fits not only RINSs, but also other isolated NSs observed by ROSAT.

As can be seen the Gould Belt *alone* can explain all observed points. As soon as velocity vectors for RINSs will be know it will be possible to calculate their exact birth places in the Belt (or, possibly, in the disk). Addition of the disk contribution gives room for few more sources at high (> 0.1 cts s^{-1}) fluxes, and for tens — at low (< 0.03 cts s^{-1}). At lower fluxes ((< 0.01 cts s^{-1}) the Galactic disk starts to dominate over the Gould Belt. The disk curve

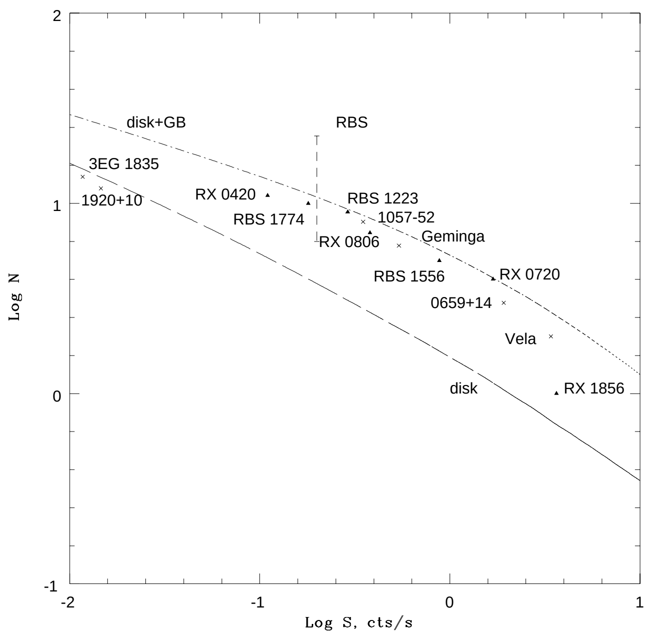

Fig. 2. All-sky Log N - Log S distribution. Black triangles — seven RINSs. Crosses — Geminga, "three musketeers", 1929+10 and 3EG J1835. We also show the RBS limit (Schwope et al. 1999). Upper curve: NSs born in the Gould Belt and in the Galactic disk ($r_{\rm disk}$ = 3 kpc, total birth rate 270 Myr^{-1}). Lower curve: only disk ($r_{\rm disk}$ = 3 kpc, birth rate 250 Myr^{-1})

alone is always below observed points (except the faintest ones — 3EG 1835 and 1929+10) and below the RBS limit (note, that RBS itself was devoted to the sources outside the galactic plane).

Absorbtion and flat geometry of NSs distribution naturaly explain very flat (< -1) Log N – Log S. In this work we do not try to fit exactly the observed data, but note, that potentially one can vary mass spectrum of NSs, NS formation rate and atmosphere model (we use simple black body) to improve the Log N – Log S distribution to get better correspondence with observations. In our opinion we make simple realistic assumption, and are able to show that even in that simple picture it is possible to explain data on isolated NSs observed by ROSAT.

Deficit of very bright ($>$ few cts s^{-1}) objects in explained by poor statistics (for example the youngest NS in our sample — Vela — could be born closer, or the brightest (the closest?) object — RX J1856 — could be younger).

Our calculations show, that there are about few dozens of unidentified close isolated NSs in ROSAT All-Sky Survey ($>$ 0.015 cts s^{-1}) depending on parameters of the model, also there can be few unidentified RINSs and fluxes $>$ 0.1 cts s^{-1} at low Galactic latitudes (see also Schwope et al. 1999). Most of objects should be observed at $\sim \pm\, 20^\circ$ from the Galactic plane towards the directions of lower absorbtion. Some of them can have counterparts among unidentified gamma-ray sources (also connected with the Gould Belt, see Grenier 2000). Identification of these objects can be important for choosing a correct cooling model and for determination of mass spectrum of NSs.

4. Discussion

In this part of the paper we briefly discuss some topics connected with properties of RINSs and other types of isolated NSs.

4.1. Local population of young NSs

Here we discuss near-by ($r < 1$ kpc) young (age$<$ 4.25 Myrs) isolated NSs.

At the present moment it is known about 20 NSs satisfying the above criteria (see Table). It includes: "magnificent seventh" (seven RINSs), Geminga and Geminga-like object 3EG J1835, "three musketeers" (Vela, 0656+14, 1055-52), 1929+10 and seven radio pulsars, which are not detected in X-rays.

The later objects are relatively old (we mention a strong "jump" in ages in between PSR 1055-52 and PSR J0056+4756; flux of PSR 1929+10 may be mainly due to non-thermal radiation). At these distances even if NSs have very low masses they are too cold now to be detected by ROSAT.

If we limit ourselves with a maximum age $\sim$ 1 Myr, then we see nearly all bright (means also low massive) cooling isolated NSs in our vicinity (see Fig. 1), the number of RINSs above $\sim$ 0.1 cts s^{-1} can be maximaly doubled.

We see, that among local young isolated NSs we have normal radio pulsars, pulsars beams of which do not pass the Earth (Geminga and probably 3EG J1835), and RINSs. Also we can expect, that around us (inside 1 kpc) there are about one hundred of isolated NSs younger than $\sim$4 Myr (some of NSs born inside 1 kpc of course can leave this volume in several Myrs). These NSs are not detected as radio pulsars, but tens of them can be identified in ROSAT data as dim sources. The beaming effect can be resposible only for part of these undetected (as radiopulsars) young NSs (about 50-70% of young pulsars are not visible from Earth (Tauris, Manchester 1998)), and most of RINSs should be really radio silent (it is difficult to construct a model in which one observes X-ray pulsations, pure black body spectrum and no signs of radio emission from a close off-beam pulsar, also one has to take into account long periods of four RINSs). It gives strong support to the arguments by Gotthelf and Vasisht (2000), that "at least half of the observed young neutron stars follow an evolutionary path quite distinct from that of the Crab pulsar".

4.2. Alignment

An interesting feature of RINSs population is an existence of periods about 5-20 seconds (typical for magnetars) for four objects and their absence for the rest three.

Table 1. Local ($r < 1$ kpc) population of young (age < 4.25 Myrs) isolated neutron stars

Object name	Period, s	Count rate, ROSAT cts/s	$\dot{P}$ $/10^{-15}$	Distance, kpc	Age^a, Myrs	Ref.
RX J185635-3754	—	3.64	—	0.117^d	~ 0.5	[1,2]
RX J0720.4-3125	8.37	1.69	$\sim 30-60$	—	—	[1,3]
1RXS J130848.6+212708 (RBS1223)	5.15	0.29	$\sim 10^4$	—	—	[1.4]
RX J1605.3+3249 (RBS1556)	—	0.88	—	—	—	[1]
RX J0806.4-4123	11.37	0.38	—	—	—	[1,5]
RX J0420.0-5022	22.7	0.11	—	—	—	[1]
1RXS J214303.7+065419 (RBS1774)	—	0.18	—	—	—	[6]
PSR B0633+17 (Geminga)	0.237	0.54^c	10.97	0.16^d	0.34	[7]
RX J1836.2+5925 (3EG J1835+5918)	—	0.015	—	—	—	[8]
PSR B0833-45 (Vela)	0.089	3.4^c	124.88	0.294^d	0.01	[7,9,10]
PSR B0656+14	0.385	1.92^c	55.01	0.762^e	0.11	[7,10]
PSR B1055-52	0.197	0.35^c	5.83	$\sim 1^b$	0.54	[7,10]
PSR B1929+10	0.227	0.012^c	1.16	0.33^d	3.1	[7,10]
PSR J0056+4756	0.472	—	3.57	0.998^e	2.1	[10]
PSR J0454+5543	0.341	—	2.37	0.793^e	2.3	[10]
PSR J1918+1541	0.371	—	2.54	0.684^e	2.3	[10]
PSR J2048-1616	1.962	—	10.96	0.639^e	2.8	[10]
PSR J1848-1952	4.308	—	23.31	0.956^e	2.9	[10]
PSR J0837+0610	1.274	—	6.8	0.722^e	3.0	[10]
PSR J1908+0734	0.212	—	0.82	0.584^e	4.1	[10]

^{a}) Ages for pulsars are estimated as $P/(2\dot{P})$,
for RX J1856 estimate of an age comes from kinematical considerations.
^{b}) Distance to J1057-52 is uncertain ($\sim$ 0.9-1.5 kpc)
^{c}) Total count rate (black body + non-thermal)
^{d}) Distances determined through parallactic measurements
^{e}) Distances determined with dispersion measure
(1) Treves et al. (2000)
(2) Kaplan et al. (2002a)
(3) Zane et al. (2002)
(4) Hambaryan et al. (2001)
(5) Haberl, Zavlin (2002)
(6) Zampieri et al. (2001)
(7) Becker, Trümper (1997)
(8) Mirabal, Halpern (2001)
(9) Pavlov et al. (2001)
(10) ATNF Pulsar Catalogue (http://wwwatnf.atnf.csiro.au/research/pulsar/catalogue/)

One explanation can be that four RINSs are magnetars. Magnetar periods are explained by magnetodipole spin-down and field decay ("period freezing", see Colpi et al. 2000). But recent observations (Zane et al. 2002, Kaplan et al. 2002b) suggest, that RX J0720 is not (and was not) a magnetar.

The fact of small pulsation fractions or there absence in RINSs also can be explained by the light bending (see discussion in Haberl, Zavlin 2002). But this mechanism works better for massive NSs, and we suspect, that RINSs are vice versa *the lightest* NSs, as far as they are relatively hot. So, it is better to find another way to explain this situation.

Vasily Beskin (2001, private communication) suggested, that it can happen due to alignment of magnetic and spin axis (see for example Tauris, Manchester 1998 for a recent discussion on alignment). Alignment is a process which also leads to a "period freezing" and low pulsation fraction (see Haberl, Zavlin 2002 for the data on pulsation fraction in RINSs).

However in the case of coolers alignment should operate on short timescale — timescale of NS cooling (~ 1 Myr). As far as for radiopulsars timescale of alignment is $\sim 10^7$ yrs (Tauris, Manchester 1998) or longer, we think, that it is unlikely that this mechanism is responsible for RINSs distribution over pulsation fraction, otherwise one has to assume that RINSs form a population separate from normal radiopulsars. For example, if we assume, that alignment timescale is $\propto (\Omega_0^2 \cos^2\alpha_0\, B_0^2)^{-1}$ (it comes from magnetodipole spin-down and condition $\Omega_0 \cos\alpha_0 = \Omega \cos\alpha$; also there can be other assumptions about alignment process, but at the moment there is no generally accepted model), then we have to assume that RINSs have different (from radiopulsars) distribution in B_0 or/and α_0, and the observed situation is just a selection efect. For example they can be a sample selected by relatively high surface temperatures, which for young NSs means by low masses.

4.3. Possible correlation between magnetic field and mass

If any part of RINSs (with or without observed pulsations) is explained by high magnetic field, then one has to explain why the fraction of magnetars is so high ($\sim 50\%$). It can be explained as a selection effect if NSs with higher magnetic fields are hotter. It can be so, if they have (on average) lower masses (below some value, which is about $1.3\, M_{\odot}$ but depends on the equation of state, direct URCA process are not allowed, and NS cooling is much slower).

The possible correlation can be explained if more massive NSs get their additional masses in the process of fall-back. In that case their magnetic field can be significantly supressed (Page et al. 1998), so more massive NSs should have lower initial magnetic fields.

For example, if we calculate so called accretion period, which separates accretor and propeller stages (Lipunov 1992), then we have:

$$P_A = 2^{5/14} \pi (GM)^{-5/7} (\mu^2/\dot{M})^{3/7},$$

here μ – magnetic moment, $\dot{M}$ – accretion rate. If we substitute $\mu = 10^{32}$ G cm^3 (typical for magnetars) and $\dot{M} = 1\, M_{\odot}$ yr^{-1} (typical for fall-back process), then we have:

$$P_A \sim 20 (M/M_{\odot})^{-5/7} (\mu_{32}^2/(\dot{M}/(M_{\odot}\, \mathrm{yr}^{-1})))^{3/7}\, \mathrm{ms}.$$

This is a typical value of a spin period for a newborn NS.

Of course, there is a question if the matter is swept out, or it is accumulated close to the magnetospheric boundary, and then accreted by the compact object. But numerical estimates (Toropin et al. 1999) suggest, that significant part of matter is swept from the propelling NS.

Vice versa, strong initial magnetic field together with fast rotation can prevent strong fall-back (it is especially possible if magneto-rotational mechanism of supernova explosion is valid, see Bisnovatyi-Kogan 1970 and Prokhorov, Postnov 2001), and may be it can also lead to long initial spin periods.

Different crust thickness and temperature of NSs of different masses can give additional correlations between mass and magnetic field, the same can be said about different properties at cores of NSs of different masses (for example, deconfinement in central parts of massive NSs, Sedrakian, Blaschke 2002).

To summarize, we can expect correlations between magnetic field and masses of NSs, and observations of RINSs can be of great importance here. Future determination of RINSs parallaxies and proper motions can help to reconstruct their kinematical history and derive their ages. It can give a clue to their mass determination basing on cooling curves (see Kaminker et al. 2002). Our results suggest, that the fraction of low massive NSs ($M <$1.3-1.4 $M_{\odot}$) can not be small, but on the other hand there should be a room for massive NSs, because other wise we overpredict the number of bright objects.

5. Conslusions and final remarks

In this paper we show, that RINSs can be naturaly explained as cooling NSs originated in the Gould Belt, so relatively high local spatial density of young NSs is due to large number of massive progenitors. As far as there are few young radio pulsars in the Solar vicinity many (about 1/2 or more) of isolated NSs should be radio quiet.

Our results show, that the fraction of NSs with masses below 1.4 $M_{\odot}$ is not small, but on the other hand it is unlikely that they form the most part of NSs population.

We find that in ROSAT All-Sky Survey it can be about few tens of unidentified RINSs. Also there can be few unidentified RINSs at fluxes > 0.1 cts s^{-1} at low Galactic latitudes.

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