BORN IN THE GOULD BELT: THE MAGNIFICENT SEVEN

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Here we explore populations of young isolated neutron stars in the Solar proximity.

We calculate Log N – Log S distribution for cooling neutron stars. On the basis of this distribution it is shown that the seven ROSAT isolated neutron stars (if they are young cooling objects) are genetically related to the Gould Belt. Our results show that there are about few tens unidentified close-by young isolated neutron stars in the ROSAT All-Sky Survey. We note that there are good reasons to suspect that the seven ROSAT neutron stars are relatively low mass objects. The possibility that masses of these stars are correlated with their surface magnetic field is also briefly discussed.

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1 Introduction

Neutron stars (NSs) and black holes (BHs) are probably the most interesting astrophysical objects. Usually NSs are observed as radio pulsars or due to accretion in close binaries. Similarly, stellar mass BHs are observed when they accrete matter from a companion star. Here we focus on much more elusive sources, namely isolated NSs, which show no radiopulsar activity.

An isolated NS can be relatively bright in soft X-rays due to its thermal emission during the first Myrs of its life, when it is still hot ($T \sim 10^6$ K) in the aftermath of the supernova (SN) explosion. Such objects are observed in the Solar proximity and in SN remnants [1]. Older NSs (that is to say those which crossed the deathline in $\approx 10^7$ yr) are not expected to emit appreciable amounts of electromagnetic radiation in any energy band. However, accretion of the interstellar medium (ISM) may make them shine again as soft, faint X-ray sources (see e.g. Treves et al. [2]). Isolated NSs might also be observed via the so-called *astrometric* microlensing with future experiments like GAIA [3] due to their high space velocities; calculations of this effect are in progress [4].

In this poster we discuss the possible origin of close-by, isolated NSs and present some evidence that the seven radio-quiet, thermally emitting ROSAT sources (the "magnificent seven" or RINSs) may be characterized by different values of the stellar parameters (mass and magnetic field) with respect to ordinary radiopulsars. We first construct the Log N – Log S distribution for young close-by isolated NSs and compare it with young isolated NSs of all types observed in the Solar vicinity. Then we discuss (following [5]) how the alignment of the magnetic and rotation axes, together with the role of fall-back following the supernova event, may help in explaining the observed parameters of NSs. We briefly comment on the possibility that the "magnificent seven" are low mass NSs ($M < (1.3 - 1.4)\, M_{\odot}$).

2 Isolated neutron stars

In this section we discuss isolated NSs. The material presented here is partly based on the results published in Popov et al. [6]. Some very recent results are also included [7].

Figure 1: The Magnificent Seven.

2.1 Origin of close-by isolated NSs

To understand how the local population of isolated NSs originated, we construct their Log N – Log S distribution. The main components of our model are: spatial distribution of NS progenitors, NS formation rate, NS cooling history, and a model of interstellar absorption (that is to say the spatial distribution of the ISM). In addition we calculate the dynamical evolution of NSs in the galactic potential. In brief our model can be described in the following way: NSs are born in the Galactic plane and in the Gould Belt (a local compound of stellar associations, see below); at birth they receive a kick velocity; we then follow the evolution of NSs in the Galactic potential; finally, we calculate the ROSAT count rate basing on cooling curves and an assumed model of interstellar absorption.

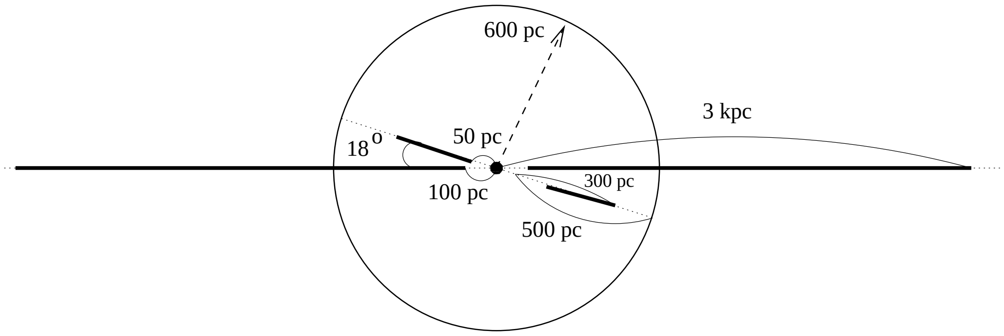

Figure 2: A sketch of the initial spatial distribution. It is a projection to the plane perpendicular to the galactic one. Stars are born in the Gould Belt, which is inclined to the galactic plane by 18 degrees, and in the galactic disc. Star producing regions are shown with thick lines.

NSs are considered to be born with a constant rate: 20 NSs per Myr come from the Gould Belt, and 250 NSs per Myr from the Galactic plane (up to a limiting distance of 3 kpc from the Sun) with a uniform distribution. The Gould Belt is modeled as a disk of 300 pc radius with an inclination of 18° with respect to the Galactic plane. Its center is situated at 100 pc from the Sun in the Galactic anticenter direction. The central region (150 pc in radius) is devoided of newborn NSs (see Pöppel [8] and Torra et al. [9]).

To calculate the thermal evolution of NSs we use the data obtained by St. Petersburg group (see Kaminker et al. [10], and the review by Yakovlev et al. [11]). The NS cooling depends on the star mass and we adopt a mass spectrum in the range $1.1\,M_\odot < M < 1.8\,M_\odot$ based on our estimates of NS mass distribution (see fig.4).

Cooling curves take into account all main neutrino emission processes but ignore neutron superfluidity. Calculations for each NS are truncated when its temperature drops to 10^5 K; this corresponds to a NS age of 4.25 Myrs for the lightest NSs ($M = 1.1\,M_\odot$) or less for more massive objects. Since we expect the NS to emit most of its luminosity at UV/soft X-ray energies interstellar absorption plays a crucial role as far as the observability of these sources is concerned. Any attempt to estimate the amount of observable cooling isolated NSs using unabsorbed flux *greatly* overestimates their number.

Our main results are presented in Fig.5 where we compare the Log N – Log S for NSs born in the Gould Belt and the Galactic disk. All curves refer to the whole sky. As can be seen the contribution from NSs born in the disk fails to explain the observed distribution while the inclusion of the objects originating

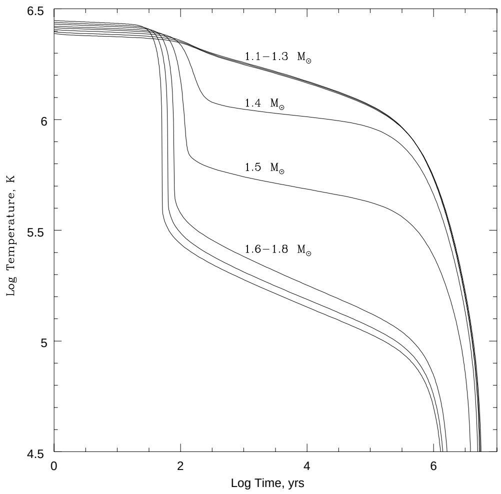

Figure 3: Cooling curves for different NS masses ([10]). Curves from top to bottom correspond to masses 1.1–1.8 $M_{\odot}$ (step $0.1M_{\odot}$). Here, and everywhere in the text, the temperature is the red-shifted surface effective temperature (i.e. that observed at infinity).

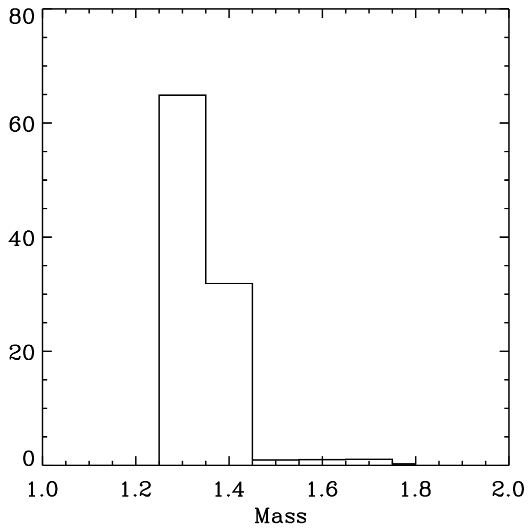

Figure 4: Mass distribution for young close-by NSs. Stars were distributed in eight bins from 1.1 to 1.8 solar masses. The vertical axis shows percentage in each bin.

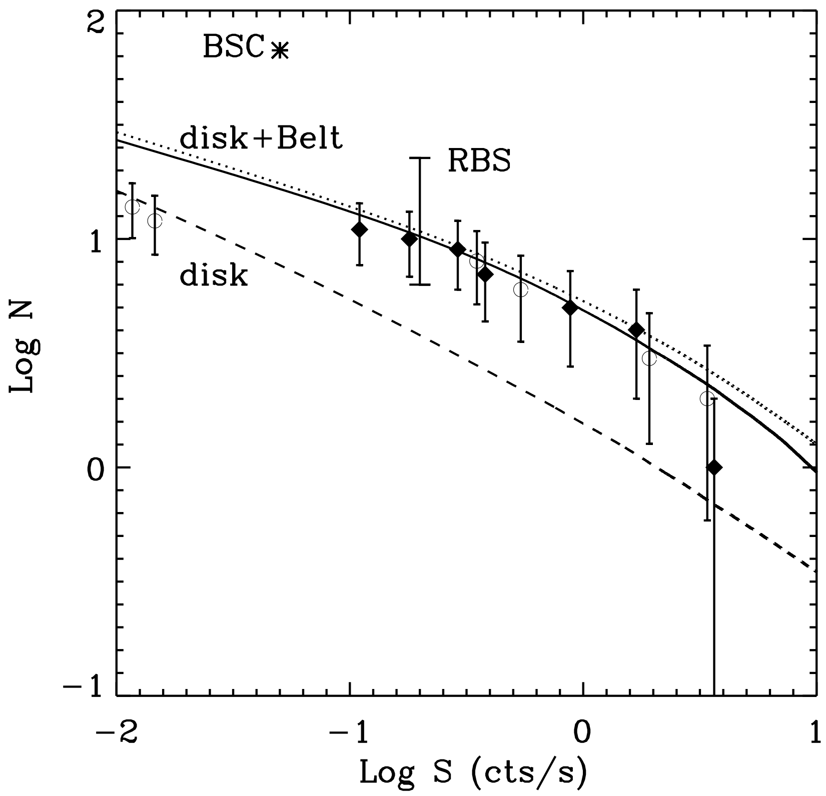

Figure 5: Solid line — a "new" model [7]: $R_{Belt} = 300$ pc, new mass spectrum, an "atmospheric effect", new kick velocity distribution from [13] in comparison with older results [6]: dotted line — disc+Belt, dashed line — only disc.

from the Gould Belt *alone* can match the observations. Absorption, the flat geometry of NS initial distribution and the finite extension of the Belt naturally explain the very flat Log N – Log S distribution.

Our calculations show that there may be at most a few dozens of unidentified close-by isolated NSs in the ROSAT All-Sky Survey (at count rate > 0.015 cts s^{-1}) depending on parameters of the model. Also there may be a few unidentified ROSAT isolated NSs (RINSs) with fluxes > 0.1 cts s^{-1} at low Galactic latitudes (see also Schwope et al. [12]). Most objects should be observed at $|b| < 20°$ towards the directions of lower absorption. Some of them can have counterparts among unidentified gamma-ray sources (also possibly connected with the Gould Belt, see Grenier [14]). Identification of

Figure 6: Projected distribution of cooling INSs in the sky in galactic coordinates. Only sources with count rate > 0.05 cts s^{-1} are accounted for. The total number of such sources is ~ 17 (see fig. 5). The plot shows contours of constant INS number density per square degree. Darker areas close to the Belt or/and to the galactic plane correspond to ~ 0.001 sources/square degree. The presence of the Belt produces a tilt in the higher projected density region which is visible in the figure.

these objects can be important for choosing a correct cooling model and for determination of the mass spectrum of NSs.

2.2 Census of close-by young NSs

At present we know about 20 isolated NSs which are younger than 4.25 Myrs and closer than 1 kpc to the Sun (see the Table). They include: the "magnificent seven" (radio-quiet, ROSAT isolated NSs with only thermal emission), Vela, the Geminga-like object 3EG J1835, the "three musketeers" (Geminga, PSR 0656+14, PSR 1055-52), PSR 1929+10 and seven young radio pulsars, which have not been detected in soft X-rays yet.

As it has been discussed in [15] and [16], the number of X-ray bright INSs is too large to be explained in terms of the average density of radio-pulsars in the Solar neighborhood. This motivated the suggestion that a sizeable fraction of NSs never become active radio emitters but left the question about the origin of the local NS population open. Here we have shown that thermally-emitting INSs are naturally explained as cooling NSs born in the Gould Belt. The relatively high local spatial density of young NSs is then due to the large number of massive progenitors in the young stellar associations which constitute the Gould Belt (see for example [17]). Our analysis lends support to the idea that RINSs (the "magnificent seven") represent the slowly cooling NSs and hence a clean sample of NSs with $M < (1.3 - 1.4)\, M_{\odot}$ ([10]).

The computed Log N –Log S distribution for X-ray thermally-emitting INSs born in the Gould Belt and (to a lesser extent) in the Galactic disk accounts for all bright INSs in the Solar vicinity (see Fig. 5) and leaves room for at most 1-2 undected sources above $\sim$ 0.1 cts s^{-1}. In addition to the observed sources, we expect about one hundred isolated NSs younger than $\sim$4 Myr inside 1 kpc. These NSs are not detected as radio pulsars, but tens of them can be identified in ROSAT data as dim sources (others are too old to be hot enough). Pulsar beaming can be responsible only for a fraction of these undetected (in the radio) young NSs (about 50-70% of young pulsars are not visible from Earth [19]), and most of RINSs should be really radio silent. This provides strong support to the arguments by Gotthelf and Vasisht [18], that "at least half of the observed young neutron stars follow an evolutionary path quite distinct from that of the Crab pulsar".

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

Object name	Period, s	CR[a], cts/s	$\dot{P}$ $/10^{-15}$	Dist., kpc	Age[b], Myrs	Ref.
RX J1856.5-3754	—	3.64	—	0.117^e	~ 0.5	[2, 22]
RX J0720.4-3125	8.37	1.69	$\sim 30-60$	—	—	[2, 24]
RX J1308.6+2127	10.3	0.29	—	—	—	[2, 25, 26]
RX J1605.3+3249	—	0.88	—	—	—	[2]
RX J0806.4-4123	11.37	0.38	—	—	—	[2, 27]
RX J0420.0-5022	22.7	0.11	—	—	—	[2]
RX J2143.7+0654	—	0.18	—	—	—	[28]
PSR B0633+17	0.237	0.54^d	10.97	0.16^e	0.34	[29]
3EG J1835+5918	—	0.015	—	—	—	[30]
PSR B0833-45	0.089	3.4^d	124.88	0.294^e	0.01	[29, 31, 32]
PSR B0656+14	0.385	1.92^d	55.01	0.762^f	0.11	[29, 32]
PSR B1055-52	0.197	0.35^d	5.83	$\sim 1^c$	0.54	[29, 32]
PSR B1929+10	0.227	0.012^d	1.16	0.33^e	3.1	[29, 32]
PSR J0056+4756	0.472	—	3.57	0.998^f	2.1	[32]
PSR J0454+5543	0.341	—	2.37	0.793^f	2.3	[32]
PSR J1918+1541	0.371	—	2.54	0.684^f	2.3	[32]
PSR J2048-1616	1.962	—	10.96	0.639^f	2.8	[32]
PSR J1848-1952	4.308	—	23.31	0.956^f	2.9	[32]
PSR J0837+0610	1.274	—	6.8	0.722^f	3.0	[32]
PSR J1908+0734	0.212	—	0.82	0.584^f	4.1	[32]

[a] ROSAT count rate
[b]) Ages for pulsars are estimated as $P/(2\dot{P})$,
for RX J1856 the estimate of its age comes from kinematical considerations [23].
[c]) Distance to PSR B1055-52 is uncertain ($\sim$ 0.9-1.5 kpc)
[d]) Total count rate (black body + non-thermal)
[e]) Distances determined through parallactic measurements
[f]) Distances determined with dispersion measure

2.3 Are RINSs of a different stock ?

An interesting feature of RINSs population is the detection of periods in the $\sim$ 10-20 s range (typical of SGRs/AXPs, i.e. of magnetars) for four objects. Present data allow to exclude any pulsation (down to a few % fraction) for at least one source, RX J1856.5-3754 [20]. V. Beskin (2001, private communication) suggested this could be due to the alignment of magnetic and spin axes. Alignment is a process which leads to "period freezing" and a low pulsed fraction (see for example Tauris and Manchester [19] for a discussion).

However in the case of coolers alignment should operate on short timescale, since the star cools down in ≈ 1 Myr. For radio pulsars the timescale of alignment is about 10 Myrs or longer [19], so it seems unlikely that this mechanism is responsible for RINSs distribution of the pulsed fraction, unless one assumes that RINSs form a population with parameters different from the same for normal radiopulsars. To illustrate this let us assume that the alignment timescale is $\tau_{align} \propto (\Omega_0^2 \cos^2\alpha_0\, B_0^2)^{-1}$ (here α_0 and B_0 are the initial values of the angle between spin and magnetic axis and of magnetic field). The previous expression comes from magnetodipolar braking supplemented by the condition $\Omega_0 \cos\alpha_0 = \Omega \cos\alpha$. To explain the difference between τ_{align} in RINSs and radio pulsars, RINSs need to have a very different distribution in B_0 and/or α_0. To have τ_{align} one order of magnitude smaller we have to have B_0 half order of magnitude larger. In this respect RINSs may come from the same population as radiopulsars but are characterized by different average properties, like e.g. higher values of the magnetic field and relatively higher surface temperatures. The latter would imply a lower mass for NSs of the same age.

Low masses of RINSs can be a natural result of their origin in the Gould Belt. Since we may assume that most of presently observed stars in the Belt were formed nearly at the same time ($>$ 20 Myrs ago) when the starformation rate was higher, then stars with masses about 8-10 $M_\odot$ are now at the end of their lives. So, all RINSs might have very similar progenitors (at least their masses are lower than a critical one – 19 $M_\odot$ [21]). And it is know, that stars with lower masses produce lower massive compact remnants (also stars with higher metallicity produce lighter remnants, which is the case of the Gould Belt, where metallicity cannot be low) [21]. In that sense *we are living in a region of the Galaxy overabundant in young low mass NSs*.

RINSs are currently thought to be rather highly magnetized objects (in RX J0720.4-3125 the detected spin-down implies $B \sim 2 \times 10^{13}$ G [24]). If this is indeed the case, then one has to explain why their B-field is a factor ~ 10 higher than the average value in radiopulsars ($\sim 2 \times 10^{12}$ G). A possibility is that NSs with higher magnetic fields are hotter. It is known that less massive NSs cools more slowly because direct URCA processes are not effective (see e.g. [11]). This means that among NSs of the same age the lighter are the hotter, so to test our hypotesis we need to show that lighter NSs may support a stronger field. Such a correlation arises quite naturally if more massive NSs get their additional mass from fall-back. In this case their magnetic field can be significantly suppressed [33], so more massive NSs should have lower initial magnetic fields. Besides, strong initial magnetic field together with fast rotation can prevent strong fall-back (this is especially possible if the magneto-rotational mechanism of supernova explosion is valid, see [34, 35]). Again this leads to the same correlation between mass and fieled strength, i.e. NSs with stronger fields would have lower masses. Also, this picture makes room for long initial spin periods. 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 [38, 39] suggest, that significant part of matter is swept from the propelling NS.

On the other hand, in the standard calculation of the magnetic field decay [36] it is shown, that for higher temperature (i.e. in our case for lower masses) we have faster field decay. Also Thompson and Murray [37] showed, that contrary to the conclusion of Page et al. it is possible that fall-back helps in field generation. In that two cases one has to expect an opposite correlation: more massive NSs have larger magnetic field. So, the situation of correlation between mass (temperature) and magnetic field is unclear.

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 [40]). The study of this (and possible other) correlation in isolated NSs may prove very useful in understanding the correct mechanism of the SN event which gave birth to these objects.

In summarizing this section, we stress that future determination of RINSs parallax and proper motion may help in tracing back their kinematical history and derive their age. It can give a clue to their mass determination basing on cooling curves (see Kaminker et al. [10]). Our results suggest that the fraction of low-mass NSs ($M \lesssim 1.3\ M_\odot$) may not be small. On the other hand there should be room for NSs with $M \gtrsim 1.4 M_\odot$, because otherwise the number of bright objects would be too large. We can also expect correlations between mass and other parameters of NSs, so RINSs can have average properties different from that of radiopulsars.

3 Conclusions

We have presented evidence that the seven radio-quiet ROSAT isolated NSs discovered so far can be connected with recent SNae explosions in the Gould Belt. These events produced nearby runaway stars and peculiar features in the local ISM including the Local Bubble. The relatively high local spatial density of young NSs is a natural consequence of the large number of massive progenitors in the Belt. The lack of a similar overabundance of active radiopulsars in the Solar vicinity lends further support to the claim that a large fraction ($\sim 50\%$ or more) of young NSs should be radio quiet. According to our results, the ROSAT All Sky Survey may contain about a few tens of unidentified RINSs. Moreover, it is possible that some unidentified RINSs with quite large flux (> 0.1 cts s^{-1}) are still hiding at low Galactic latitudes (see fig. 6).

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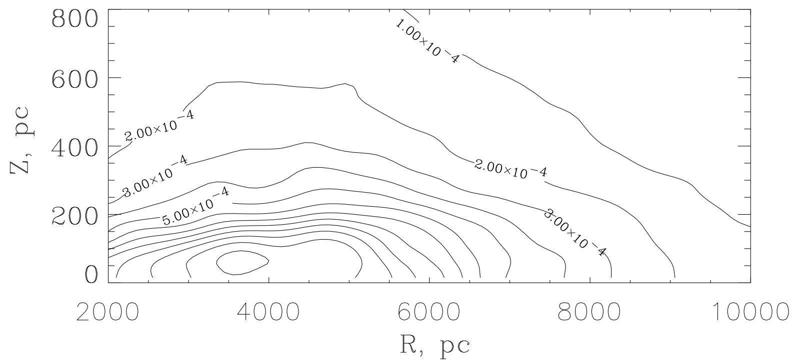

Figure 7: Distribution of all isolated NSs in the Galaxy in the $R-z$ plane. The data is calculated by a Monte Carlo of >10000 individual tracks on a fine grid (10 pc in z direction and 100 pc in R direction). Curves were smoothed, all irregularities are of statistical nature. Kick velocity is assumed following [13]. NSs are born in the thin disc with semithickness 75 pc. No NS born inside $R = 2$ kpc and outside $R = 16$ kpc are taken into account. NS formation rate is assumed to be proportional to the square of the ISM density at the birthplace. Results are normalized to have in total 5 10^8 NSs born in the described region. Density contours are shown with a step 0.0001 pc^{-3}.

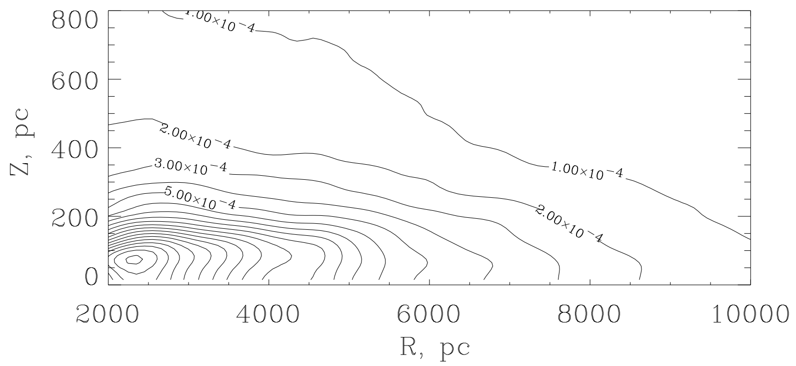

Figure 8: Distribution of all isolated NSs in the Galaxy in the $R-z$ plane. All parameters are as in the previous figure except the distribution of NS formation rate, it is asusmed to be proportional to $[\exp(-z/75\,\mathrm{pc})\exp(-R/4\,\mathrm{kpc})]$. Curves were smoothed as in the previous picture. Is it clearly seen that in that case NSs are stronger concentrated towards the galactic center, then in the case of NS formation rate proportional to the square of the ISM density.