YOUNG CLOSE-BY NEUTRON STARS: THE GOULD BELT VS. THE GALACTIC DISC

S.B. POPOV[1,2], R. TUROLLA[1], M.E. PROKHOROV[2], M. COLPI[3] and A. TREVES[4]
[1]*Universitá di Padova, Dipartimento di Fisica, via Marzolo 8, 35131 Padova, Italy;*
E-mail: polar@sai.msu.ru
[2]*Sternberg Astronomical Institute, Russia*
[3]*Università di Milano-Bicocca, Italy*
[4]*Università dell'Insubria, Italy*

(Received 05 September 2004; accepted 18 October 2004)

Abstract. We present new population synthesis calculations of close young neutron stars. In comparison with our previous investigation we use a different neutron star mass spectrum and different initial spatial and velocity distributions. The results confirm that most of ROSAT dim radioquiet isolated neutron stars had their origin in the Gould Belt. We predict that about several tens of young neutron stars can be identified in ROSAT All Sky Survey data at low galactic latitudes. Some of these sources also can have counterparts among EGRET unidentified sources.

Keywords: stars: neutron, stars: evolution, stars: statistics, X-ray: stars

1. Introduction

Over the last decade X-ray missions revealed an increasing number of isolated neutron stars (INSs) in the solar vicinity. Many of these sources, essentially discovered by ROSAT, are not observed as active radio pulsars and show quite peculiar emission properties, both at X-ray and optical wavelengths (see, e.g. Treves et al., 2000; Becker and Pavlov, 2002; Haberl, 2004 for recent reviews). Their spectrum is peaked at $\sim$100 eV and is well described in terms of a featureless blackbody. The optical emission (when observed, see e.g. Kaplan et al., 2003 on the case of RX J0720-3125) appears close to a Rayleigh-Jeans distribution but lies well above the extrapolation of the X-ray blackbody to optical wavelengths.

The many puzzling features of X-ray emitting INSs offer contrasted views about their nature. Although several interpretations have been proposed (in terms of old INSs accreting the interstellar medium, decaying magnetars or even quark stars), the more conservative explanation is that they are conventional middle-aged ($\approx 10^5$–10^6 years) cooling NSs which for reasons not understood as yet fail to be detected as radio emitters.

A possible problem with this latter scenario is connected with the observed overabundance of these sources in the solar proximity with respect to what predicted by population synthesis models. If INSs are born in the galactic disc (at about the

Astrophysics and Space Science **xxx:** 1–11, 2004.

solar distance from the galactic center) at the same rate at which radio pulsars are formed and if they follow a standard cooling history then the number of detectable X-ray sources falls short of the observed one by about a factor a few (Neuhäuser and Trümper, 1999; Popov et al., 2000). A possible solution is to invoke a recent epoch of enhanced NS formation in $\lesssim$1 kpc around the Sun. Originally this idea has been suggested by Grenier (2000) and Gehrels et al. (2000) in connection with the possibility that unidentified EGRET sources are young close-by NSs. The Gould Belt, a collection of young star associations which encompasses the Sun, appears the most likely birthplace for the majority of these NSs (see the Belt description in Pöppel, 1997). In Popov et al. (2002) it was suggested that INSs observed by ROSAT as dim X-ray sources can be explained as young cooling objects originated mainly from the Gould Belt. Very recently Popov et al. (2003) (hereafter Paper I) addressed this issue in detail by means of a population synthesis model in which NS formation in the Belt (in addition to that in the galactic disc) was properly accounted for.

In this paper we present some refinements to the results of Paper I. In particular we explore the effects of modifying and relaxing some of the original assumptions contained in Paper I on the computed $\log N - \log S$ of cooling NSs. A central point in this respect is the assumed NS mass spectrum since the cooling evolution is very sensitive to the star mass. However, as it is shown, new results largely agree with previous ones and offer further support to the idea that the Gould Belt is the nursery of the local NS population.

2. Model

The details of our model have been presented in Paper I; its main features are summarized below. We assume that NSs are continuously born in the galactic disc (up to a distance of $\sim$3 kpc from the Sun) and in the Gould Belt at a constant rate (see Figure 1). The rates are different in the disc and in the Belt and have been estimated from available SN progenitors counts (Tammann et al., 1994; Grenier, 2000). Both the spatial and the cooling history of newborn NSs is then followed as they evolve

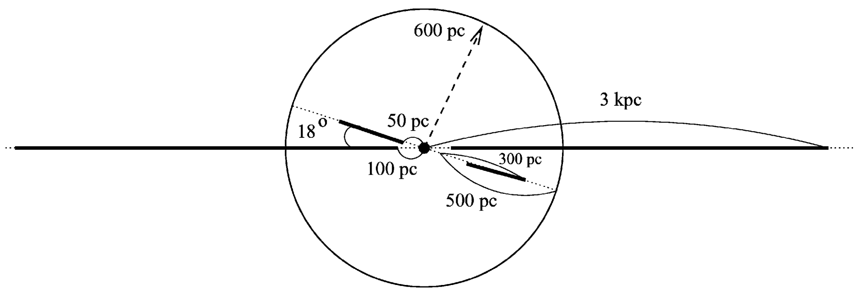

Figure 1. A sketch of the initial spatial distribution. It is a projection to the plane perpendicular to the galactic one. Stars are born in the Gould Belt, which is inclined to the galactic plane by 18 degrees, and in the galactic disc. Star producing regions are shown with thick lines.

in the galactic potential. Typically we calculate $\sim 10^4$ evolutionary tracks and then normalize our results to the actual number of NSs born in the considered volume ($\sim$1000 NSs in a sphere of radius 3 kpc centered on the Sun) during a 4.25 Myrs time interval. NSs cooling curves by Kaminker et al. (2002) have been used to derive the NS temperature at each time step. The duration of the calculation is fixed by the request that the surface temperature of the lightest (i.e. the hottest) NSs is higher than 10^5 K. Cooler NSs could not have been detected by ROSAT even if they are as close as 10 pc. Since young cooling NSs are expected to emit most of their luminosity at UV/soft X-ray energies ($\sim$20–200 eV, corresponding to temperatures $\sim 10^5$–10^6 K), interstellar absorption must be accounted for. The PSPC count rate is finally obtained from the unabsorbed flux, which corresponds to the given temperature, radius and distance of the star, and from the value of the column density. This allows us to construct the $\log N - \log S$ curve for close-by, cooling NSs.

Results presented in Paper I rely on a particular choice for a set of free parameters which enter the model. They reflect our incomplete knowledge of some properties of the NS population, and are mainly related to: (i) the spatial distribution of NS progenitors; (ii) the NS mass distribution; (iii) the NS kick velocity distribution; (iv) the NS emitted spectrum. In Paper I we assumed that NSs are uniformly born in the Belt, modeled as a thin disc 500 pc in radius, and that their initial velocity distribution is represented by a single maxwellian with a mean velocity of 225 km s^{-1}. The mass spectrum was taken to be flat in the mass range $1.1\,M_\odot \leq M \leq 1.8\,M_\odot$. Cooling NSs were assumed to emit a pure blackbody spectrum without allowance for possible deviations arising from reprocessing in an atmosphere and/or by a reduce surface emissivity.

Here we address all these points in more detail. In particular we assess the effects of relaxing the assumptions of Paper I on the computed $\log N - \log S$ curve. The main changes are described below. As it will be shown in the next section, the original results presented in Paper I are not much influenced. With respect to Paper I we introduce four modifications.

- We use a slightly different spatial distribution of NS progenitors taking the Gould Belt radius to be 300 pc (instead of 500 pc, see Figure 1). The total birthrate in the Belt was the same.
- Natal kicks were drawn from the complete velocity distribution of Arzoumanian et al. (2002), described by two maxwellians with total average velocity $\sim$540 km s^{-1}, instead of a single maxwellian with average velocity $\sim$225 km s^{-1}.
- We account for the possible reduced emissivity of the star surface, as suggested by the case of RX J1856.5-3754 (e.g. Drake et al., 2002). This has been mimicked using a radiation radius $R_{\rm rad} \sim 0.32R$, so that $L = 4\pi R_{\rm rad}^2\,\sigma T_{\rm eff}^4 \sim 0.1 L_{\rm BB,R}$.[1]

[1] Such a strong reduction of emissivity of course influences cooling curves. However, we do not attempt to take into account self-consistently in this paper. A self-consistent calculations will be presented separetly. Also possible influence of an atmosphere should be taken into account.

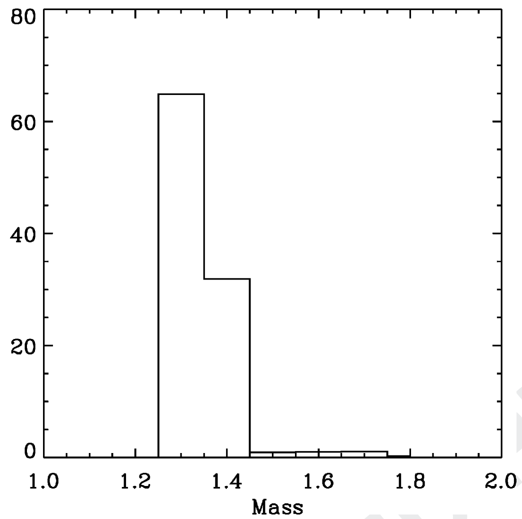

Figure 2. Mass distribution for young close-by NSs. Stars were distributed in eight bins from 1.1 to 1.8 solar masses. The vertical axis shows percentage in each bin.

– A more realistic mass spectrum of NSs, peaked around 1.3–1.4 $M_\odot$ (see Figure 2), has been derived and incorporated in the simulations instead of the flat one used before.

This last point requires some more comments. Performing a population synthesis of cooling NSs demands for the NS mass spectrum, since cooling curves depend on mass (e.g. Kaminker et al., 2002). As noted by Woosley et al. (2002), at present models do not allow a precise determination of the NS mass spectrum. However, given the dependence of the cooling curves on mass (see below), even a rough estimate is enough for the case at hand. In our calculations we use cooling curves for NS masses in the range $1.1\ M_\odot < M < 1.8\ M_\odot$; masses are grouped in eight bins. Cooling models show that there is a critical value for the mass ($\sim$1.35 $M_\odot$ in the case of Kaminker et al. (2002), the exact value depends on model assumptions) across which the cooling history significantly changes. NSs with masses below the critical value have similar cooling histories and remain hot for a relatively long time ($T = 10^5$ K after 4.25 Myrs). Intermediate mass stars ($\sim$1.4–1.5 $M_\odot$) cool down to 10^5 K in about the same time but have lower temperatures during the first million years of their evolution in comparison with less massive stars. NSs with masses $M > 1.5\ M_\odot$ experience much faster cooling and become completely invisible (at X-ray energies) in a few hundred thousand years or even earlier.

To our end, the most important point is estimating the number of NSs above and below the critical mass. In our discrete description this amounts to assess the number of stars in the first three mass bins relative to remaining five. In order to do so, we proceed as follows. At first we take massive stars closer than 500 pc (i.e. with known parallax >0.002) from the Hipparcos catalog ESA, 1997. Stars from B2 to O8 are considered here to be NS progenitors. Spectral classes presented in the catalog are then transformed into masses, although we are aware that this is a very rough procedure. NS masses are finally obtained from the model described in Timmes et al. (1996) and Woosley et al. (2002). To do it we use a fit of Figure 14 in Woosley et al. (2002) and assumed that all stars less massive than $\sim$11 $M_\odot$ produce NSs of the same mass, i.e. 1.27 $M_\odot$. In all other cases the baryonic NS mass is calculated from the mass of the progenitor according to

$$M_{\rm bar} = \begin{cases} 0.067\, M + 0.567 & 11\, M_\odot < M < 15\, M_\odot \\ {\rm const} = 1.567 & 15\, M_\odot \le M \le 20\, M_\odot \\ 0.0867\, M - 0.167 & M > 20\, M_\odot. \end{cases} \tag{1}$$

The NS gravitational mass (which is used in our calculation) is calculated according to $M_{\rm bar} - M_{\rm grav} = 0.075 M_{\rm grav}^2$ (Timmes et al., 1996), here and in the formula below masses are in the solar units. All stars from the solar proximity contributed to the final distribution with some coefficient, inversely proportional to their lifetime ($\log t = 9.9 - 3.8 \log M + \log^2 M$).

Within the 500 pc sphere the number of progenitors with $M < 13.85\, M_\odot$ (which give a 1.35 $M_\odot$ NS) is about twice higher than expected from the Salpeter mass function. Such an enhancement is mostly connected with the Gould Belt. We find that about 2/3 of NSs have mass $<$1.35 $M_\odot$ and that most NSs fall into the 1.3 and 1.4 $M_\odot$ bins (see Figure 2). The contribution of massive ($>$1.5 $M_\odot$) NSs is negligible (about 3% by number). This is a special feature of the solar proximity.

This mass spectrum is in reasonable correspondence with mass determinations in binary radio and X-ray pulsars. We note, that the peak at 1.3 $M_\odot$ is due to the assumption (see Timmes et al., 1996) that all NSs below $\sim$11 $M_\odot$ produce NSs of nearly the same mass, $\sim$1.27 $M_\odot$. However, smearing the peak over the first three mass bins would produce about the same results for $\log N - \log S$ since the cooling curves for these masses are very similar in the time interval of interest for our calculations (see Kaminker et al., 2002). Although it represents just a rough estimate, this spectrum is better, in our opinion, than the flat one we used before, being closer to the one obtained from the mass determinations in binary systems (mostly in binary radio pulsars), and in general it is in better correspondence with expectations about young NSs in the solar vicinity.

3. Results

3.1. Log *N*–Log *S* curves

The $\log N - \log S$ distributions for young cooling INSs originated from the Gould Belt and circumsolar parts of the galactic disc have been calculated for different parameters characterizing the NSs mass, velocity, and spatial distributions. The final variant, shown in Figure 5, includes all the four modifications discussed in the previous section. For comparison observational points representing the log $N -$ log S distribution of isolated close-by NSs are also shown. These sources include three small groups of INSs: the seven ROSAT radioquiet INSs ("the Magnificent seven"), four young close-by radio pulsars with detected thermal radiation ("the three musketeers" and PSR B1929 + 10) and Geminga together with the Geminga-like object 3EG J1835 + 5918 (see Paper I for details). The "Magnificent seven" is characterized by absence of detected radio emission and long spin periods (about 5–10 s). Geminga and 3EG J1835 + 5918 are known γ-ray sources.

Symbols for the observed data are in correspondence with the type of the faintest object which contributes at a given flux (filled: ROSAT radioquiet INSs, empty: other sources). That is if the faintest object at a given flux is one of the magnificent seven then we plot a filled diamond, if not – an empty circle. Error bars represent poissonian errors. The two limits on the number of INSs in the ROSAT data obtained by Rutledge et al. (2003) (labeled BSC) and Schwope et al. (1999) (labeled RBS) are also shown.

Let us discuss first the relative effect of each of the four modifications mentioned above. Clearly, a reduced surface emissivity and higher average kick velocity act in decreasing the number of observable sources at a given flux, while a higher fraction of low mass (i.e. hotter) NSs and a more compact initial distribution tend to increase it.

In Figure 3 we compare our previous result for the disc alone and disc + Belt with the new ones for disc + Belt. To obtain these new curves we considered either a smaller radiation radius and flat mass spectrum (dot-dot-dashed curve) or the new mass spectrum together with standard emissivity (dot-dashed curve). One can see that the reduced emissivity and the new peaked mass spectrum move the log $N -$ log S curve (down and up, respectively) by nearly half order of magnitude each, with a net combined effect of slightly decreasing the number of observable sources. Here the spatial distribution of NS progenitors and kick velocities are the same as in the original calculations. From the next figure (Figure 4) it is apparent that the same effect is produced when a more compact initial distribution and higher kick velocities are introduced, keeping the original assumptions about the star emissivity and mass spectrum. Together these two modifications tend to slightly increase the number of observable sources.

Our final results for log $N -$ log S are presented in Figure 5. Here all four effects are taken into account. The general conclusion is that modifications do not change our results significantly. Our estimate is well below the BSC limit by Rutledge et al. (2003) and in correspondence with the RBS limit (Schwope et al., 1999).

3.2. Spatial distribution

In this section we briefly discuss the spatial distribution of observable INSs. Despite the main focus of our work has been of the log $N -$ log S curve, the present distribu-

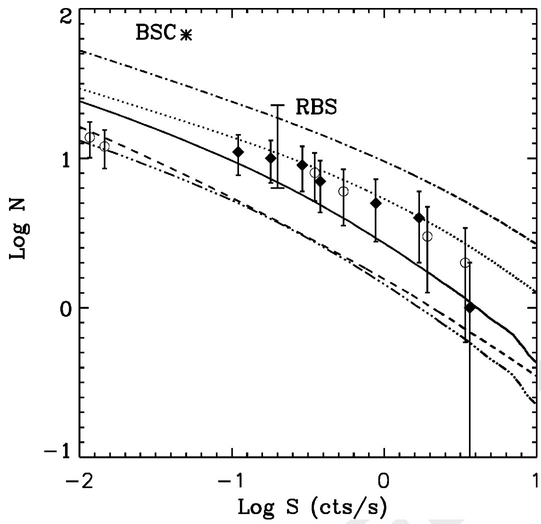

Figure 3. Relative contribution of the "atmospheric effect" and mass spectrum are shown. Dotted line – the "old" model for disc + Belt contribution. Dashed line – the "old" model without a Gould Belt. Dot-dot-dashed (the lowest line) – "atmospheric effect." Dot-dashed – effect of the new mass spectrum. Solid line – both effects together. Symbols which show observational points (filled diamonds or open circles) are in correspondence with the type of the faintest object (a ROSAT INS or not) which contributes to the total number at the specified count rate (see text for more details). RBS and BSC are limits on the number of bright INSs in ROSAT data obtained by Schwope et al. (1999) and Rutledge et al. (2003), respectively.

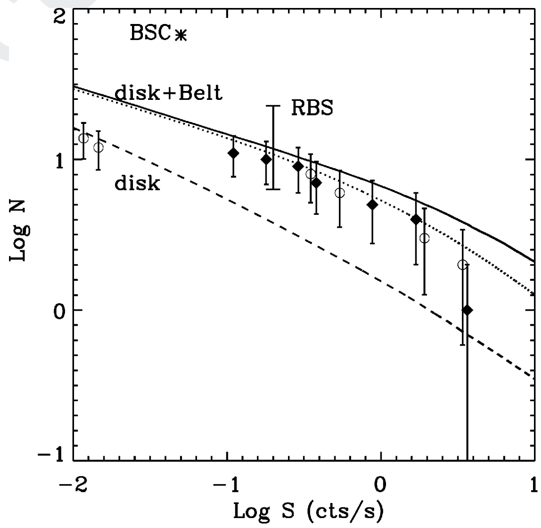

Figure 4. Contributions of variations of initial spatial distribution and kick velocity distribution are shown. Solid line: $R_{\rm Belt} = 300$ pc and kick velocity distribution as in Arzoumanian et al. (2002).

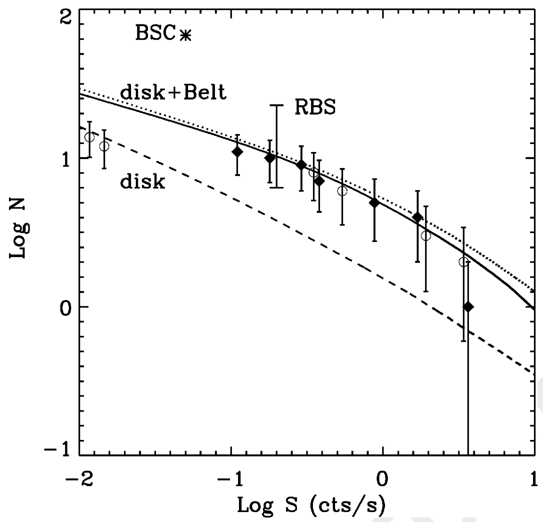

Figure 5. A "new" model (solid line: $R_{\rm Belt} = 300$ pc, new mass spectrum, an "atmospheric effect", new kick velocity distribution) in comparison with older results (dotted line – disc + Belt, dashed line – only disc).

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 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.

tion of cooling INSs on the sky is obtained as a by-product of our evolutionary code. For illustrative purposes we report in Figure 6 the projected spatial distribution of relatively bright coolers (count rate > 0.05 PSPC cts s^{-1}) in galactic coordinates. In the figure we present contours of constant number of INS. The galactic plane and the Gould Belt are clearly visible. High-latitude regions are nearly free of young NSs.

This result should be taken with care as far as we used a simplified initial spatial distribution for the progenitors and did not take into account any detailed ISM structure around the Sun. The figure just illustrates some general features of the distribution. The two main features of our model are appearent from the plot of Figure 6 which shows that the highest projected density of sources is close to the galactic plane. The presence of the Belt produces the tilt of the high density region towards low galactic latitudes. All small scale details are due to individual tracks of calculated INSs and should not be treated as predictive of any "fine structure."

As expected, sources are strongly concentrated towards the galactic plane and the Gould Belt. Only about 12% of sources with ROSAT count rate >0.01 cts s^{-1} are found at $|b| > 40^{\circ}$. About 20% of sources lie outside the belt $\pm 30^{\circ}$ from the galactic plane, while $\sim$50% are expected to be within $\pm 12^{\circ}$ from the plane of the Galaxy (brighter sources are more strongly concentrated towards the galactic plane and the Gould Belt since they correspond to younger INSs). Although the very strong concentration towards the galactic plane may reflect the assumption that NSs are born exactly in the (infinitesimally thin) galactic disc, the source distribution at higher latitudes should be real.

Finally we would like to stress that the distribution of young NSs around the Sun is definitely different from the full NS spatial distribution, which is dominated by old stars (age $>10^7$ years). For comparison the latter is shown in Figures 7 and 8 for two different assumptions about NS formation rate distribution.

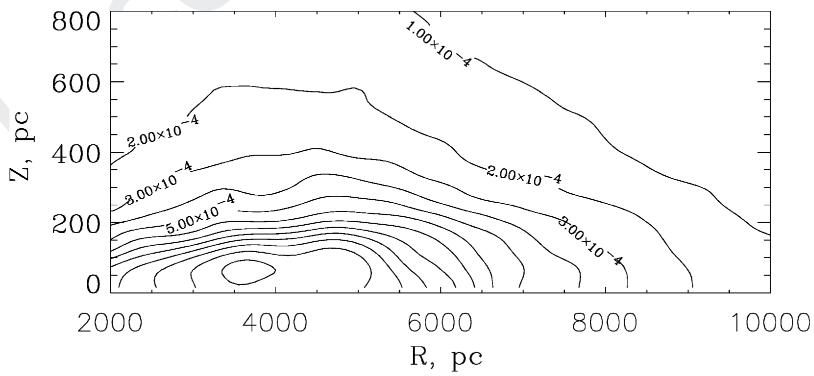

Figure 7. Distribution of all isolated NSs in the Galaxy in the R–z plane. The data is calculated by a Monte Carlo of $>$10,000 individual tracks on a fine grid (10 pc in z direction and 100 pc in R direction). Curves were smoothed, all irregularities are of statistical nature. Kick velocity is assumed following Arzoumanian et al. (2002). 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}.

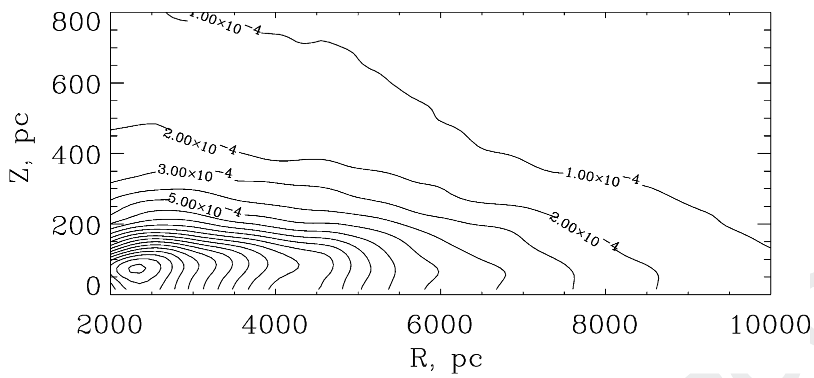

Figure 8. Distribution of all isolated NSs in the Galaxy in the *R*–*z* plane. All parameters are as in the previous figure except the distribution of NS formation rate, it is asusmed to be proportional to $[\exp(-z/75\,\mathrm{pc})\exp(-R/4\,\mathrm{kpc})]$. Curves were smoothed as in the previous picture. 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.

We do not expect new identifications of bright (>0.1 cts s^{-1}) cooling INSs at large galactic latitudes. Most of the unidentified ROSAT objects (still there should be tens of them for count rates >0.01 cts s^{-1}) should be in crowded fields at $\pm 30^\circ$ from the plane of the Milky Way. Some can be identified as EGRET sources among which young INSs from the Gould Belt should be numerous (Grenier, 2000).

4. Conclusions

In this paper we presented results of more advance population synthesis model (in comparison with Paper I) of young close-by INSs. Account of new effects does not change our previous conclusion that observed cooling INSs in the solar vicinity originated in the Gould Belt.

We also modeled distribution of bright cooling close INSs on the sky. Most of them are situated close to the galactic plane and to the plane of the Gould Belt.

More detailed calculation are necessary. It is especially important to take into account effects of the most outer layers of NSs on the spectrum and detailed distribution of NS progenitors. After parameters of a population synthesis model are fixed it is possible to use $\log N - \log S$ distribution as an independent test of models of thermal evolution of NSs.

Acknowledgements

We want to thank Dmitry Yakovlev and his colleagues for putting their cooling model to our disposal, and Hovik Grigorian for very useful comments. SP also thanks Isabelle Grenier, David Blaschke and Dima Voskresensky for discussions. The work of MP and SP was partly supported by the RFBR grant 03-02-16068 and by the program "Universities of Russia" grant 02.03.013/2. The work of MC, SP, AT and RT was partially supported by the Italian Ministry for Education, University and Research (MIUR) under grant COFIN-2000-MM02C71842.

References

Arzoumanian, Z., Chernoff, D.F. and Cordes, J.M.: 2002, *ApJ* **568**, 289.

Becker, W. and Pavlov, G.G.: 2002, in: J. Bleeker, J. Geiss and M. Huber (eds.), The Century of Space Science, Kluwer Academic Publishers.

Drake, J.J., Marshall, H.L. et al.: 2002, *ApJ* **573**, 996. **Q1**

ESA: 1997, ESA SP-1200.

Gehrels, N., Macomb, D.J., Bertsch, D.L., Thompson, D.J. and Hartman, R.C.: 2000, *Nature* **404**, 363.

Grenier, I.A.: 2000, *A&A* **364**, L93.

Haberl, F.: 2004, *Adv. Space Res.* **33**, 638.

Kaminker, A.D., Yakovlev, D.G. and Gnedin, O.Yu.: 2002, *A&A* **383**, 1076.

Kaplan, D.L., van Kerkwijk, M.H., Marshall, H.L., Jacoby, B.A., Kulkarni, S.R. and Frail, D.A.: 2003, *ApJ* **590**, 1008.

Neuhäuser, R. and Trümper, J.E.: 1999, *A&A* **343**, 151.

Popov, S.B., Prokhorov, M.E., Colpi, M., Treves, A. and Turolla, R.: 2000, *ApJ* **544**, L53.

Popov, S.B., Prokhorov, M.E., Colpi, M., Treves, A. and Turolla, R.: 2002, *Gravit. Cosmol*, **8**(Suppl. II), 133 (astro-ph/0201030).

Popov, S.B., Prokhorov, M.E., Colpi, M., Treves, A. and Turolla, R.: 2003, *A&A* **406**, 111 (Paper I).

Pöppel, W.: 1997, *Fund. Cosm. Phys.* **18**, 1.

Rutledge, R.E., Fox, D.W., Bogosavljevic, M. and Mahabal, A.: 2003, *ApJ* **598**, 458.

Schwope, A.D., Hasinger, G., Schwarz, R., Haberl, F. and Schmidt, M.: 1999, *A&A* **341**, L51.

Tammann, G.A., Löffler, W. and Schröder, A.: 1994, *ApJS* **92**, 487.

Timmes, F.X., Woosley, S.E. and Weaver, T.A.: 1996, *ApJ* **457**, 834.

Treves, A., Turolla, R., Zane, S. and Colpi, M.: 2000, *PASP* **112**, 297.

Woosley, S.E., Heger, A. and Weaver, T.A.: 2002, *Rev. Modern Phys.* **74**, 1015.

Queries

Q1. Author: Please provide the complete list of authors.