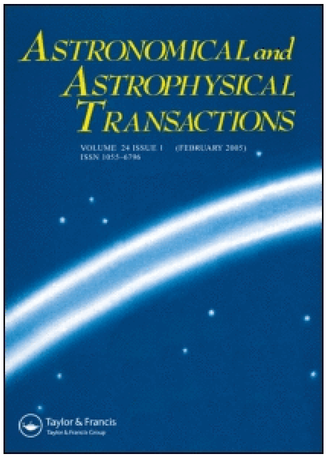

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Dim ROSAT isolated neutron star candidates

S. B. Popov [a]; M. Colpi [b]; M. E. Prokhorov [a]; A. Treves [c]; R. Turolla [d]
[a] Sternberg Astronomical Institute, Moscow, Russia
[b] University of Milan, Milan, Italy
[c] University of Insubria, Como, Italy
[d] University of Padova, Padova, Italy

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DIM ROSAT ISOLATED NEUTRON STAR CANDIDATES: OLD ACCRETORS OR YOUNG COOLERS?

S. B. POPOV[†], M. COLPI[*], M. E. PROKHOROV[†], A. TREVES[**], and R. TUROLLA[††]

[†] *Sternberg Astronomical Institute Universitetskii pr.13, 119899, Moscow, Russia*
e-mail: polar@sai.msu.ru; mystery@sai.msu.ru
[*] *University of Milan Via Celoria 16, 20133 Milan, Italy*
e-mail: colpi@uni.mi.astro.it
[**] *University of Insubria Via Lucini 3, 22100, Como, Italy*
e-mail: treves@mi.infn.it
[††] *University of Padova Via Marzolo 8, 35131 Padova, Italy*
e-mail: turolla@pd.infn.it

We model populations of isolated neutron stars in order to investigate them as progenitors of dim soft X-ray sources. We discuss both: old accreting and young cooling neutron stars. For accretors realistic magneto-rotational evolution and evolution in the Galactic potential are taken into account together with a realistic large scale distribution of the interstellar medium. Cooling neutron stars are explored with a simpler model of local sources, but interstellar absorption is additionly taken into account. In the standard assumptions (maxwellian initial velocity distribution with the mean value about 200–300 km s^{-1}, initial magnetic field distribution similar to radiopulsar, no field decay, small initial spin periods) we obtain accretors only if their magnetic field is $> 10^{11}$–10^{12} G. So, for polar cap accretion X-ray sources are relatively hard with typical temperature about 300–400 eV. For them interstellar absorption is not very significant, and we predict about 1 source per square degree for fluxes about 10^{-15}–10^{-16} erg cm^{-2} s^{-1} for energy range 0.5–2 keV. For young cooling neutron stars, which are soft sources ($T \sim 50$ eV), absorption is very important, and they are significantly less abundant at low fluxes. For them we predict < 0.1 sources per square degree. With these standard assumptions we cannot explain observed properties of the ROSAT candidates (relatively large number of close bright sources; low temperatures; periods about 10–20 s, which are observed for two candidates: RX J0420.0–5022 and RX J0720–3125). We argue, that most part of these sources can be young cooling neutron stars with typical age about 10^6 yrs or less, if the total number of neutron stars in the Galaxy is significantly higher, than it comes from radiopulsars statistics. The source RX J0420.0–5022 with the spin period 22.7 s can't be explained as a 'standard' accretor or a 'standard' cooling neutron star. In this case most probably magnetic field decay is operating.

KEY WORDS Accretion – stars: kinematics – stars: neutron – stars: magnetic field – X-rays: stars

1 INTRODUCTION

The existence of isolated accreting neutron stars (IANSs) among observed X-ray sources is still under doubt. Also the nature of 6–7 ROSAT INS candidates is unclear (Treves *et al.*, 2000), and two competive hypothesis (accretion and cooling) exist.

Here we try to explore in more detail this situation, and to give some predictions for observations at very low fluxes with such satellites as Chandra and XMM (Newton).

In our previous paper (Popov *et al.*, 2000, P2000 hereafter) we didn't discuss $\log N$–$\log S$ distribution for IANSs. In the present paper we make an attempt to do it.

In Section 2 we describe calculations of $\log N$–$\log S$ for IANSs. In general they are similar to calculations in P2000, but some differences exist and we briefly discuss them.

In Section 3 we describe a simple model which was used to obtain $\log N$–$\log S$ distribution for cooling INSs with interstellar absorption.

In Section 4 we discuss all these results, and in the last section we present our conclusions.

2 ACCRETING ISOLATED NEUTRON STARS

Population synthesis of IANSs in the Galaxy and similar investigations were made previously by different authors (see, for example, Treves and Colpi, 1991 (TC91 hereafter), Manning *et al.*, 1996; Madau and Blaes, 1994). This attempt is closely connected with our previous work (P2000). In the following subsection we briefly discuss the model we use, and differences with the previous work.

2.1 Model

In general the present model is similar to the one used in P2000. INSs are born in the Galactic plane. In our calculations they are initially uniformly distributed in some range of radii from the Galactic center, but for each point a coefficient (weight) proportional to the square of the local interstellar medium (ISM) density is calculated, and all statistics are calculated for a specified track with this weight. So, in our calculations starformation rate is proportional to the square of the ISM density and is constant in time. If there was initial starformation burst in our Galaxy, when significant part of INS population was formed, then our results should be shifted towards higher number of accretors.

In order to increase statistics we make calculations only for initial positions from which a NS with initial velocity about 100 km s^{-1} (or less) can appear in the volume for which $\log N$–$\log S$ is calculated. For different volumes we take different ranges of birth places.

We don't use a spatial grid as in P2000, instead we input a timestep, i.e. all parameters of an INS are recalculated not on the grid cell boundaries, but with after some timeinterval, δt. It is different for different stages of NSs evolution and different regions of the Galaxy. The timeinterval is shorter for short living stages (propeller and georotator) and inside the volume, where $\log N$–$\log S$ is calculated. Typical value of the timestep – 10^5 yrs.

Each track is used for NSs of different ages, i.e. it is 'shifted' in time. So, a single track actually represents a population of NSs born in the same place with the same initial conditions, but at different moments: from the birth of the Galaxy to the present time. Number of these 'shifts' can be roughly estimated as $T_{\rm calc}/T_{\rm step} \sim 10^5$, where $T_{\rm calc} = 10^{10}$ yrs – the age of the Galaxy.

ISM distribution, as previously, is taken from Bochkarev (1992) and Zane *et al.* (1995).

The important feature of our approach is detailed calculation of magneto-rotational evolution of INSs. Magneto-rotational evolution is calculated as before, but critical periods (ejector period, $P_E(E \to P)$, for ejector $\to$ propeller transition; ejector period, $P_E(P \to E)$, for propeller $\to$ ejector transition; accretor period, P_A) are very slightly changed:

$$\begin{aligned} P_E(E \to P) &= 10.21 s \mu_{30}^{1/2} n^{-1/4} v_{10}^{1/2}, \\ P_E(P \to E) &= 2.623 s \mu_{30}^{4/7} n^{-2/7} v_{10}^{6/7}, \\ P_A &= 302.105 s \mu_{30}^{6/7} n^{-3/7} v_{10}^{9/7} M_{1.4}^{-11/7}. \end{aligned}$$

Here μ_{30} – magnetic moment in units 10^{30} G cm^3, v_{10} – INS's spatial velocity in 10 km s^{-1}, n – ISM concentration, $M_{1.4}$ – INS's mass in units 1.4 $M_\odot$.

For spindown on the ejector stage we use the following equation:

$$P = P_0 + 3 \times 10^{-4} t^{1/2} \mu_{30},$$

where t is in yrs and as usual $\mu = 1/2 B_p R_{NS}^3$(R_{NS} – NS's radius, B_p – polar magnetic field).

For the propeller stage we use, as in P2000, Shakura's formula (Shakura 1975). At the accretor stage spin period is set to be equal to the 'equilibrium' period (Lipunov and Popov, 1995; Konenkov and Popov, 1997). We don't take into account the possibility of formation of temporal accretion disk around accreting INS, when its velocity relative to ISM is small. It should have significant influence on spin periods, p, and $\dot{p}$ distribution of IANS (and 'equilibrium' periods can be slightly different from the values we use), but it is not the question of this paper (from the point of view of luminosity and spectrum it can be very important, for example, for isolated accreting black holes, which are not discussed here).

We assume high accretion efficiency: $L = \dot{M} GM/R_{NS}$, which is reasonable for accretion onto NSs at low accretion rates. We don't take into account any effects of heating of the accreting matter by radiation of the IANS.

Galactic potential is also taken in the same form as in P2000, but parameters are slightly changed in order to fit better solar distance from the Galactic center, which is assumed to be equal to 8.5 kpc (see Madau and Blaes, 1994).

Initially a NSs has a circular velocity, with a value corresponding to its birthplace, and additional kick velocity, which had a maxwellian distribution, is added.

To increase statistics (we are able to calculate about 15000 tracks, compare with $\sim$ 1000 in P2000) we calculate only low-velocity stars (v $<$ 100 km s^{-1}) from the maxwellian distribution for the mean velocity about 300 km s^{-1} (calculations for different mean kick velocities are presented in P2000). All INSs with initial velocities $>$ 100 km s^{-1} are assumed to be on the ejector stage (or much less probably on the propeller or on the georotator stages). This assumption is based on the estimate:

$$t_E \sim 10^{10} \mathrm{yrs}\, \mu_{30}^{-1} n^{-1/2} v_{100},$$

and on the note, that very strongly magnetized INSs (which are able to leave the ejector stage in less than 10^{10} yrs even for high spatial velocities) can leave the propeller stage not as accretors, but as georotators.

Our results can be easily renormalized for any mean velocity $>$ 200 km s^{-1} (for 200 km s^{-1}, for example, $\log N$–$\log S$ curve should be higher by a factor of 3.12 than it is for the mean velocity 300 km s^{-1}, for which we plot all our graphs here).

Magnetic fields of INSs are taken to have log-gaussian distribution, similar to the radiopulsar magnetic field (in contrary to P2000, where we used only two single values of the initial magnetic field). For each track we calculate 6 different magneto-rotational histories (for 6 different values of initial magnetic fields), and then results are merged and normalized according to this log-gaussian distribution:

$$f(\mu) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(\lg\mu - \lg\mu_0)^2/(2\sigma^2)},$$

where $\mu = 1/2 B_p R_{NS}^3$, R_{NS} – NS's radius, B_p – polar magnetic field; $\sigma = 0.32$, $\lg\mu_0 = 30.06$ (which corresponds to $\lg B_0 = 12.36$). Our results are sensitive to the initial field distribution.

Nearly all strongly magnetized INSs come to the stage of accretion, and for $\log N$–$\log S$ we obtain good statistics for fluxes $< 10^{-11}$ erg cm^{-2} s^{-1}. For higher fluxes our results can be well extrapolated as a line with the slope $-3/2$.

All our results are normalized for the total number of NSs in the Galaxy $N = 10^9$ (see discussion on this number below).

2.2 Results

Our main results are presented in Figures 1 and 2.

To compare calculations with observations it is useful to produce $\log N$–$\log S$ distribution. In P2000 we could produce only a very naive $\log N$–$\log S$, plotting our single point (for limiting distance 140 pc and limiting flux 10^{-13} erg cm^{-2} s^{-1}) and adding lines with slopes -1 and $-3/2$. It is clearly well below observed points (see Fig. 2) due to a small volume ($r < 140$ pc) for which the number of bright accretors was estimated. Here we try to obtain realistic $\log N$–$\log S$ for IANSs. We calculate $\log N$–$\log S$ only for stars in some vicinity of the Sun (two values were used: 500 pc and 5 kpc).

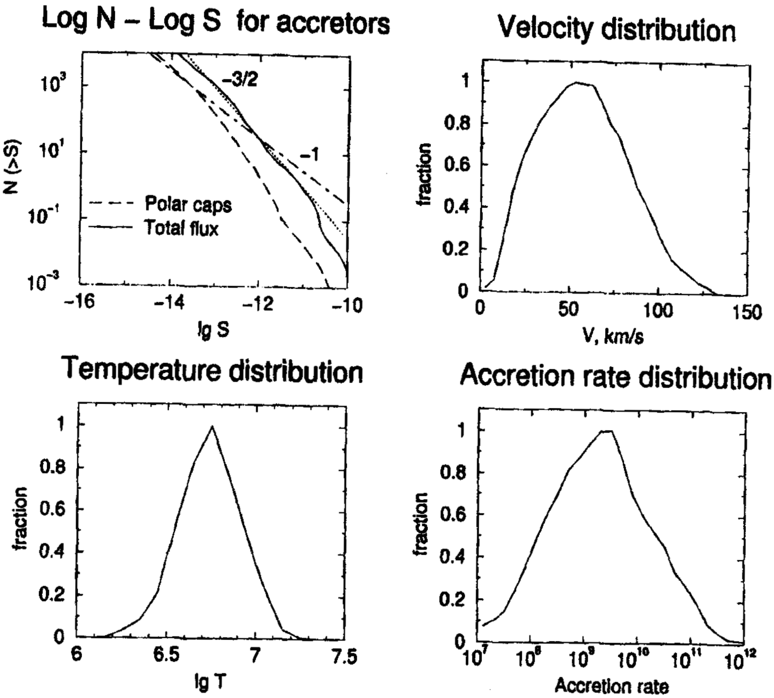

Figure 1 On the upper left panel we show $\log N$–$\log S$ distribution for accretors inside 5 kpc sphere around the Sun. Two curves are shown: for the total flux, and for polar cap black-body emission in the range 0.5–2 keV. For comparison we add lines with the slopes −1 and −3/2. On the upper right panel we show distribution of velocities of all accretors in our calculation. On this panel (as on all others) distribution is normalized to be equal to 1 in the maximum, and log-gaussian distribution of the magnetic field is taken into account. On the lower left panel we show temperature distribution for polar cap accretion. Maximum corresponds to $\lg T \sim 6.8$. And on the last panel we show $\dot{M}$ distribution. Maximum corresponds to the accretion rate $\sim 10^{9.5}$ g s^{-1}.

In the Figure 1 we show $\log N$–$\log S$ distribution for accretors inside 5 kpc sphere around the Sun and distributions of temperature, velocity and accretion rate for *all* accretors, which appear in our calculations. In all graphs the realistic initial magnetic field distribution is taken into account. Mostly all strong magnetic field NSs in our calculations, i.e. for $v < 100$ km s^{-1}, become accretors. But the plotted distribution are mainly determined by the most abundant NSs in the accepted population with fields about 2×10^{12} G. INSs with fields $< 0.5 \times 10^{11}$ G never appears as accretors in different runs of the program.

The brightest accretors have luminosities about 10^{32} erg s^{-1}, but the majority of them has luminosities about 10^{29}–10^{30} erg s^{-1}.

To compare results with ROSAT sources we use conversion factor 0.01 cts s^{-1} $= 3 \times 10^{-13}$ erg cm^{-2} s^{-1} (Neühauser and Trümper 1999, NT99 hereafter). Calculations show, that for relatively high fluxes ($> 10^{-12}$–10^{-13} erg cm^{-2} s^{-1}) we can

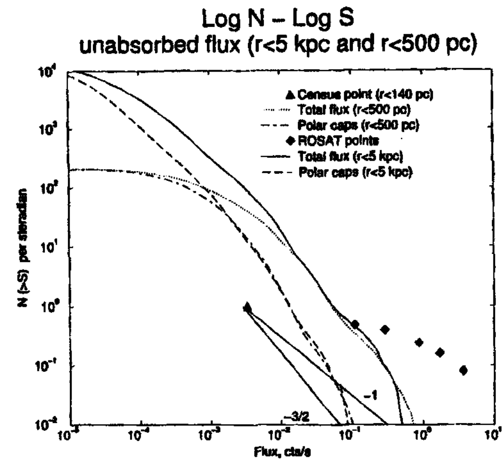

Figure 2 On the figure we compare log N–log S for 500 pc and 5 kpc spheres around the Sun. Also we plot log N–log S for observed sources and naive log N–log S based on calculations in P2000 ('census point').

use results for 500 pc vicinity, as far as they are undistinguished from 5 kpc sample (only for very bright sources we don't have enough statistics for 5 kpc sample).

We calculate $\log N$–$\log S$ distribution for the total flux ($L = \dot{M}GM/R_{NS}$, $S_{\rm total} = L/4\pi r^2$) and flux in the range 0.5–2 keV for polar cap accretion. In the later case the spectrum is assumed to be black-body and polar cap radius is calculated with known magnetic field and accretion rate ($R_{\rm cap} = R_{NS}\sqrt{R_{NS}/R_A}, R_A$ – Alfven radius).

Flattening of the $\log N$–$\log S$ curves (Fig. 2), which are calculated in the 500 pc vicinity, shows that nearly at $f < 10^{-14}$ erg cm^{-2} s^{-1} we see significant part of all accretors in that volume. Steep decrease of $\log N$–$\log S$ at very high fluxes appears simply due to low statistics for bright (i.e. rare: very close or very low velocity) sources.

If absorption is negligible, then one expects about 1 source per square degree for the range 0.5–2 keV for limiting fluxes about 10^{-16}–10^{-15} erg cm^{-2} s^{-1} (i.e. about 3.4×10^4 sources for the whole sky, but they should be significantly concentrated to the Galactic plane, and asymmetry center-anticenter should also appear).

We also compare our new results with P2000 when it is possible, and both sets of results are in very good correspondence.

3 COOLING NEUTRON STARS

Cooling INSs can be a reasonable explanation for ROSAT INS candidates. But, as for accretors, in that case some problems also exist.

3.1 Model

We assume, that INSs are uniformly distributed in the disk with a semithickness of 450 pc. Spatial density of INSs was varied. We take two values: $n_{NS} = 0.33 \times 10^{-3}$ pc^{-3} and $n_{NS} = 3.3 \times 10^{-3}$ pc^{-3}. The first value corresponds to the density which was used, for example, in NT99, and it is connected with the radiopulsar statistics. The second value corresponds to the total number of NSs in the Galaxy $N \sim 10^9$ and comes from nucleosynthesis calculations (Arnett *et al.*, 1989). This higher value was used, for example, in TC91. These two values can be compared, for example, with $n \sim 1.4 \times 10^{-3}$ pc^{-3} in Paczynski (1990). For high kick velocities the value $n_{NS} = 3.3 \times 10^{-3}$ pc^{-3} seems to be high, but as we show below it is necessary to explain the observed data.

All INSs are taken as the 'standard candles' with $L = 10^{32}$ erg s^{-1} and black-body spectrum. Time of NS cooling was taken to be 10^6 yrs. It corresponds to the 'slow cooling' (Page *et al.*, 2000). In the 'fast cooling' models (Yakovlev *et al.*, 1999) numbers of observable cooling INSs should be much smaller. So, potentially, observations of INSs can help to distinguish between models of cooling of NSs.

ISM is treated in a very simple way:

1. spherical Local Bubble of radius r_l (it can be varied) and density $n = 0.07$ cm^{-3} around the Sun.

2. uniform ISM with density $n = 1$ cm^{-3} in the disc with 450 pc semithickness.

After the column density, N_H, is calculated we run standard ROSAT routine to calculate count rate for a given luminosity, temperature and column density.

This simple model reproduces the most important feature: 'flattening' of $\log N$–$\log S$ distribution outside the Local Bubble, which is important to explain the ROSAT data for bright fluxes. More sophisticated models with realistic distribution of ISM and INSs give nearly the same results, and more detailed study of $\log N$–$\log S$ for coolers will be presented in a separate paper.

3.2 Results

Results are shown in Figures 3 and 4. In the first of them we plot observed sources, calculations for accretors and a line from NT99. The later one is obtained with an assumption of a total NSs number about (1–3)$\times 10^8$ and has the slope -1. Curves for accretors are plotted for 10^9 INSs in the Galaxy. For comparable numbers it is clear, that at bright fluxes coolers dominate. It happens due to much higher average luminosity of coolers (10^{32} vs. 10^{29}–10^{30} erg s^{-1}).

In the second – we add two our curves for coolers for different spatial densities of INSs, which were calculated with absorption in the way described in the previous subsection, instead of the curves for accretors.

In these calculations we take $r_l = 140$ pc (equal to the radius of the Local Bubble in our calculations for accretors), which is in the range suggested by Sfeir *et al.* (1999).

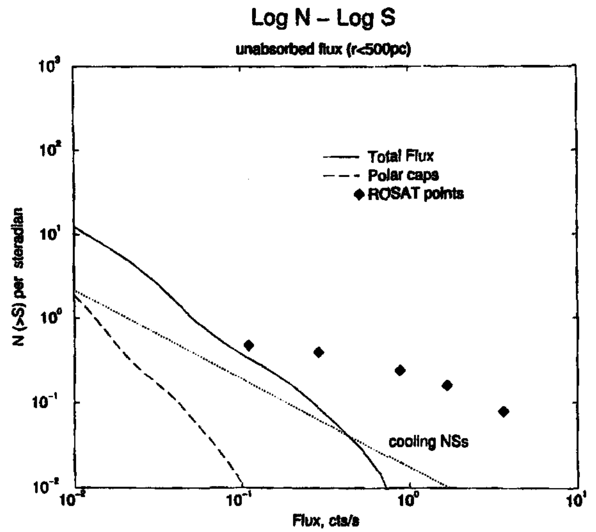

Figure 3 Here we show bright part of calculated $\log N$–$\log S$ for accretors. Fluxes are converted to count rate. For comparison we show observed sources and a line with the slope -1 proposed in NT99 as a simple estimate of $\log N$–$\log S$ for cooling INSs.

A clear 'knee' appears due to absorption. Such strong flattening can help to explain the observed data, if one assumes, that most of INS are identified, as far as we deal with relatively bright sources (> 0.1 cts s^{-1}).

The position of the 'knee' can be fitted varying r_l and densities in and outside the Local Bubble. When r_l is smaller the 'knee' moves to the right, to higher count rates.

We note, that one also can play with other parameters: time of the cooling, luminosity distribution of INSs etc. Especially, time of the cooling is important, as far as there is some evidence for a shorter value of this parameter ('fast cooling' models). Increase of luminosity of cooling INSs can also help to explain the data without very significant increase of INSs number, but any way, this number should be higher, than it comes from the radiopulsar statistics.

In general, if we take high spatial density of INSs, then we can explain in this model both: the number of bright sources and the 'flattening' of the observed $\log N$–$\log S$ distribution.

4 DISCUSSION

The task to explain ROSAT observations of INS candidates is not an easy one, as far as all 'standard' assumptions can't produce enough of such sources:

1. Bright (high count rates, > 0.1 cts s^{-1}).

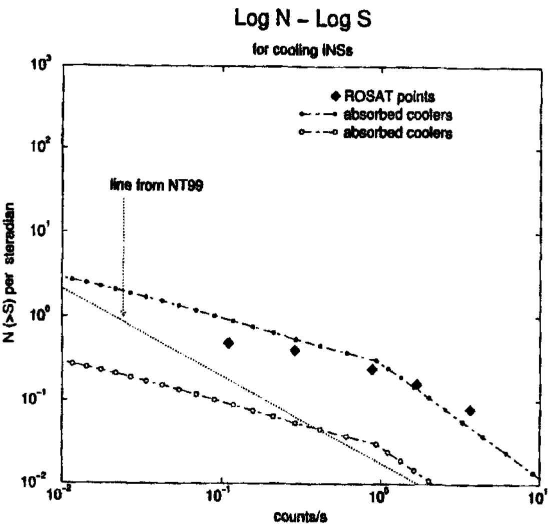

Figure 4 *The same as in the previous figure, but we add our calculations of* $\log N$*–*$\log S$ *for* cooling NSs instead of calculations for accretors. Our upper (filled circles) curve for coolers corresponds to NSs density 0.0033 pc^{-3}. And lower (opaque circles) – to 0.00033 pc^{-3}; r_l = 140 pc.

2. Close (low $N_H \sim 10^{20}$ cm^{-2}).

3. Soft ($T \sim$ 50–100 eV).

4. With spin periods about 10–20 s (two candidates have periods of 8.4 and 22.7 s).

Polar cap accretion for 'standard' magnetic field ($\sim 10^{12}$ G) can't produce so soft sources, and so short periods are impossible for those field values (period of accretion, p_A, is $\sim$ 100–1000 s). Young NSs can't slow down to $\sim$ 20 s in $< 10^6$, (when they are still hot) for, 'standard' fields and even for fields about 10^{14} G ($p \sim 15\text{sec}\, B_{14}(t/10^6 \text{ yrs})^{1/2}$).

If we assume, that all NSs are initially active as radiopulsars, it gives us, that the total number of NSs in the Galaxy is about (1–3)$\times 10^8$ (we exclude possible initial starformation burst). For these numbers one can't have enough bright INSs in the solar vicinity for both: accretion and cooling scenarios.

So, we need something 'non-standard' in order to explain ROSAT candidates as one unique population:

1. *Higher numbers of NSs in the Galaxy.* In this case coolers can explain high number of bright close sources and their temperatures. But it is difficult to explain the observed periods. And if the cooling time is significantly shorter than the value we use 'fast cooling' models), then it is impossible to explain high number of bright sources even for high total number of INSs. To obtain reasonable number of accretors higher total number of INSs in the Galaxy ($\sim 10^9$) is also necessary.

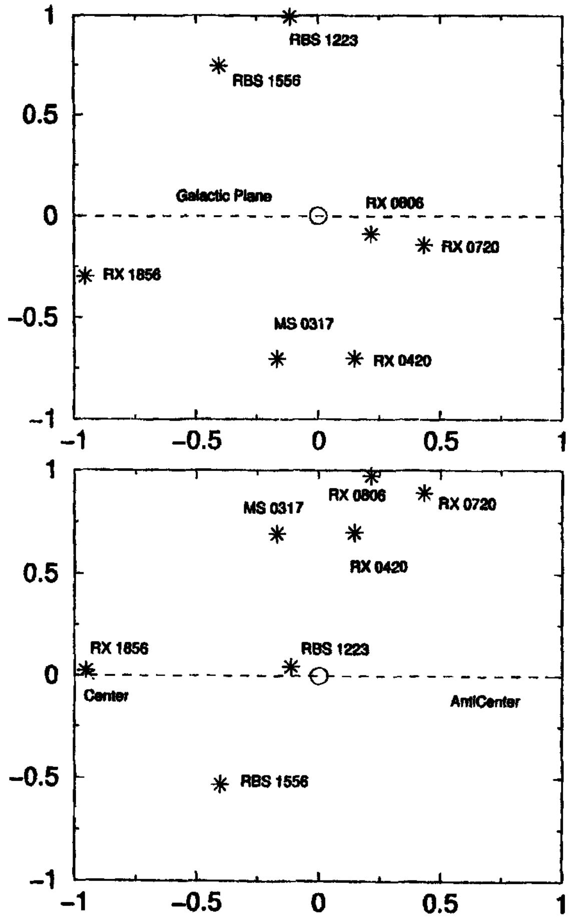

Figure 5 Distribution of ROSAT INS candidates in the Galaxy. For all sources the unit distance was accepted. On the upper panel x–z distribution is shown (projection to the plane perpendicular to the Galactic plane), and on the lower – x–y distribution (projection onto the Galactic plane).

Note, that actually in the cooling model it is necessary to have only *local* (both in time and space) excess of INSs relative to radiopulsar statistics. Such excess is in correspondence with historical SN rate (van den Bergh and Tammann, 1991). Also the structure of local ISM (Local Bubble, North Polar Spur etc.) and even geophysical data (isotope history in antarctic ice etc.) favors recent close SN explosions, but we don't know close ($d < 100$ pc) young ($t < 10^6$ yrs) radiopulsars. Close regions of starformation (Sco–Cen association and Perseus–Taurus association) can be birth places of these young INSs.

2. *Magnetic field decay.* In this scenario accretors can explain low temperatures and periods. We are not sure about exact numbers of close bright sources: to obtain

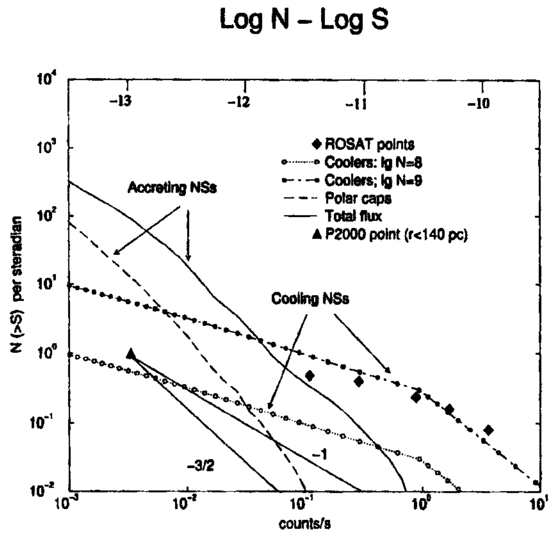

Figure 6 Combined figure of different log N–log S for bright sources. We show our calculations, observational points and the naive log N–log S distribution from P2000 calculations.

them it is necessary to produce population synthesis calculations. Field decay can both: increase and decrease numbers of accretors (see Colpi *et al.*, 1998; Livio *et al.*, 1998, P2000). INSs, in general, can be very important for models of field decay (see Popov and Prokhorov, 2000). In these objects field decay appears in the most 'pure' form (Konenkov and Popov, 1997; Wang, 1997), as far as strong accretion from the secondary companion does not influence the process of field decay. Extensive calculations of population synthesis of IANSs with realistic models of field decay and taking into account ISM absorption (these accretors should be soft, so absorption is important) are necessary.

3. ***Strong decaying magnetic fields.*** It can help to explain in the cooling model periods of candidates. And if decaying field can increase the lifetime of such an object as bright X-ray source, it can also help to explain numbers without huge increasing of the total number of INSs. But detailed population synthesis is necessary, because this hypothesis should be also in correspondence with other observations of NSs (radiopulsars, close binaries, compact X-ray sources in supernova remnants (SNR) etc.), so probably the fraction of strong field stars cannot be high, and relatively high number of observed bright candidates can be unexplained in this model.

In principle, one can also play with non-standard distributions of spin periods (long initial period, longer than in Spruit and Phinney, 1998) or initial magnetic fields (second maximum on very low values, $\sim 10^7$ G, or on high values, $\sim 10^{14}$ G). There is no observational (and even theoretical) evidence for high numbers of NSs with so unusual period distribution. Probable high numbers of NSs with strong magnetic fields were discussed by several authors (see, for example, Gotthelf and Vasisht, 2000). These authors argue, that 'at least half of the observed young neutron stars follow an evolutionary path quite distinct from that of the Crab pulsar', i.e. they most probably have strong (magnetar scale) initial magnetic fields, which are decaying in order to produce observed luminosity (which cannot be explained by magnetodipole losses). Probably, there can be INSs with strong initial magnetic field, which is not significantly decaying on short time scale, so they'll spin-down as magnetars, but their X-ray luminosity will be 1–2 orders of magnitude lower. For our knowledge nobody tried to make population synthesis of close binary stars including about 50% magnetars with field decay at the rate which is necessary to produce enough X-rays. It should be done, because otherwise we are not sure, that wonderful idea about magnetars is 'universal'.

Observations of Cas A (Chakrabarty *et al.*, 2000; Pavlov *et al.*, 2000) showed a central compact X-ray source which is not a classical young pulsar, and, most probably, it can't be a magnetar. There is a possibility, that this NS was born with a very low ($< 10^8$ G) magnetic field. So, 'low-field' hypothesis also can be discussed.

Anyway, the enigma of ROSAT candidates and IANSs should have solution, which is in correspondence with radiopulsars observations, observations of NSs in close binaries, AXPs, and compact radiosilent sources in SNRs (also the small number of radiopulsars in SNRs should be taken into account). All, probably bright, ideas, which satisfy only part of the data are not very useful, and one must think about influence of every accepted hypothesis on all known populations of NSs.

It is difficult to explain the ROSAT data simply increasing the number of IANSs (for example, decreasing mean velocity of population, or taking non-maxwellian velocity distributions). It is so, because accretors have wide distribution of temperatures and velocities and they are hotter and dimmer on average than coolers, so the flattening of the $\log N$–$\log S$ due to absorption (even if for some reasons sources are soft as coolers) is not so significant, and at 0.1 cts s^{-1} (and brighter) one expects significant number of sources (hundreds), which are not identified as INS candidates for some reasons.

We also note, that due to wider distributions in temperature towards higher values accretors can dominate at low fluxes, when one reaches distance, where all coolers are completely absorbed, but the most hot and bright accretors still can be observed.

We don't take into account very detailed (and complicated) structure of the local ISM. Probably, that discovery of hot (300–400 eV) accretors in close molecular clouds with deep Chandra observations is possible as far as absorption is not as important for them as for softer sources discussed previously (Colpi *et al.*, 1993; Manning, *et al.*, 1996), but of course due to large initial mean velocity numbers should be smaller than predicted previously by Colpi *et al.* (1993). Note, that in this new picture molecular clouds are not the best places to search for IANSs, because new satellites can observe very dim sources, and the most important point is to have a large sample, i.e. to observe sources at large distances, not in close molecular clouds, which obscure distant sources behind them. Bright ROSAT candidates, being close (and not numerous) sources, don't show any concentration to the Galactic plane or to the Galactic center (see Fig. 5). For fainter sources this concentration should be observed. Usually deep pointings are made in the direction perpendicular to the Galactic plane (see for example, Mushotzky *et al.*, 2000). In these observations we don't expect a lot of accretors (only the closest ones can appear: far from the Galactic plane there is no fuel for accretion). The same is true for coolers, because even if in principle a cooler can be observed from large distance if absorption is low, a young NS can't travel farther than ~ 1 kpc from the Galactic plane during its cooling time, and even if halo is filled with INSs, they are old cold objects, non-emitting X-rays.

5 CONCLUSIONS

We modeled populations of INSs in order to investigate them as possible dim X-ray sources (especially in the ROSAT data). We discussed both: old accreting and young cooling NSs (see Fig. 6). For accretors realistic magneto-rotational evolution and evolution in the Galactic potential were taken into account together with realistic large scale distribution of the ISM. Cooling neutron stars were explored with a simpler model of local sources, and interstellar absorption was taken into account also in a simplified way.

In the standard assumptions (maxwellian initial velocity distribution with the mean value about 200–300 km s^{-1}, initial field distribution similar to radiopulsar, no magnetic field decay, small initial spin periods) we obtained accretors only if INS's magnetic field was $> 10^{11}$–10^{12} G. So, for polar cap accretion X-ray sources were relatively hard with typical temperature about 300–400 eV. For them interstellar absorption is not very significant (on the scale of hundreds pc), and we predict about 1 source per square degree for fluxes about 10^{-15}–10^{-16} erg cm^{-2} s^{-1} for energy range 0.5–2 keV, which can be observed, for example, by Chandra. As far as at low fluxes IANSs will show concentration towards the Galactic plane (and the Galactic center) our average prediction of 1 per square degree should be nearly an order of magnitude higher for regions close to the Galactic plane, and correspondently lower for direction perpendicular to this plane.

Number of coolers can not be high at these low fluxes due to strong absorption of these very soft objects (mean free path ~ 100 pc).

We note also, that accretors can appear as dim sources not only because they are very far, but because of wide luminosity distribution. Coolers vice versa have very 'sharp' luminosity distribution, and dim coolers should be far (not close, but with low luminosity), which means strong absorption.

So, we predict ~ 0.01–0.1 coolers per square degree in deep Chandra observations. Which means, that it is nearly impossible to find them serendipiously in these pointings with very small covered area of the sky.

If XMM (Newton) is able to observe in deep (200 ks) pointings all coolers with $T \sim 10^6$ K inside 5 kpc (Helfand, 1998), than the prediction will be about 1 per square degree also for coolers. This is an average value, and in direction towards the Galactic center of course it'll be higher (as for accretors).

Anyway, number of accretors (of all luminosities) in the Galaxy is about two orders of magnitude larger than the number of observable coolers (few percents vs.

0.01%). But an 'average' accretor is 3 orders of magnitude dimmer than a typical cooler.

Accretors become more abundant than coolers at fluxes about 10^{-13}–10^{-12} erg cm^{-2} s^{-1}. But we note again, that these accretors are hotter than coolers (300–400 eV vs. 50–100 eV).

With standard assumptions we can't explain observed properties of the ROS AT candidates (large number of close bright sources, low temperatures, periods about 10 s) in the frame of the accretion scenario. We argue, that most part of these sources can be young cooling neutron stars with typical age about 10^6 yrs, if the total number of INSs in the Galaxy is much higher, than it comes from radiopulsar statistics. So, probably X-ray observations of INS candidates are in favor of high number of NSs in the Galaxy, most of which never were active as radiopulsars. This conclusion is in correspondence with nucleosynthesis investigations (Arnett *et al.*, 1989) and observations of SNRs (Gotthelf and Vasisht, 2000).

The source RX J0420.0-5022 with spin period 22.7 s can't be explained as a 'standard' accretor or a 'standard' cooling neutron star as far as its period is not typical for both of these populations. In this case most probably magnetic field decay is operating.

So, to explain ROSAT data on INSs candidates one have to introduce some 'non-standard' (but reasonable and relatively popular) ideas about NSs astrophysics.

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References

Arnett, W. D., Schramm, D. N., and Truran, J. W. (1989) *Astrophys. J.* **339**, L25.

Bochkarev, N. G. (1992) *Basics of the ISM Physics*, Moscow, Moscow University Press.

Brazier, K. T. S. and Johnston, S. (1998) *Mon. Not. R. Astron. Soc.* **305**, 671.

Chakrabarty, D. *et al.* (2000) *Astrophys. J.* **548**, 800.

Colpi, M, Campana, S., and Treves, A. (1993) *Astron. Astrophys.* **278**, 161.

Colpi, M., Turolla, R., Zane, S., and Treves, A. (1998) *Astrophys. J.* 501, 252.

Gotthelf, E. V. and Vasisht, G. (2000) In: M. Kramer, N. Nex, N. Wielebinski (eds.) *Pulsar Astronomy-2000 and Beyond, AIP Conf. Ser. V.* **202**, 699 (astro-ph 9911344).

Hansen, B. M. S. and Phinney, E. S. (1997) *Mon. Not. R. Astron. Soc.* **291**, 569.

Helfand, D. J. (1998) *Mem. Soc. Astron. Ital.* **69**, 791.

Konenkov, D. Yu. and Popov, S. B. (1997) *PAZh* **23**, 569.

Lipunov, V. M. and Popov, S. B. (1995) *Astron. Zh.* **71**, 711.

Livio, M., Xu, C., and Frank, J. (1998) *Astrophys. J.* **492**, 298.

Madau, P., and Blaes, O. (1994) *Astrophys. J.* **423**, 748.
Manning, R. A., Jeffries, R. D., and Willmore A. P. (1996) *Mon. Not. R. Astron. Soc.* **278**, 577.
Mushotzky, R. F., Cowie, L. L., Barger, A. J., and Arnaud, K. A. (2000) *Nature* **404**, 459.
Neühauser, R. and Trümper, J. E. (1999) *Astron. Astrophys.* **343**, 151 (NT99).
Paczynski, B. (1990) *Astrophys. J.* **348**, 485.
Page, D., Geppert, U. and Zannias, T. (2000) *Astron. Astrophys.* **360**, 1052.
Pavlov, G. G. *et al.* (2000) *Astrophys. J.* **531**, L53 (astro-ph/9912024).
Popov, S. B. and Prokhorov, M. E. (2000) *Astron. Astrophys.* **357**, 164.
Popov, S. B., Colpi, M., Treves, A., Turolla, R., Lipunov, V. M. and Prokhorov, M. E. (2000) *Astrophys. J.* **530**, 896 (P2000).
Shakura, N. I. (1975) *PAZh* **1**, 23.
Sfeir, D. M., Lallement, R, Crifo, F. and Welsh, B. Y. (1999) *Astron. Astrophys.* **346**, 785.
Spruit, H. and Phinney, E. S. (1998) *Nature* **393**, 139.
Treves, A., and Colpi, M. (1991) *Astron. Astrophys.* **241**, 107.
Treves, A., Turolla, R., Zane, S., and Colpi, M. (2000) *PASP* **112**, 297.
Wang, J. (1997) *Astrophys. J.* **486**, L119.
van den Bergh, S. and Tammann, G. A. (1991) *ARAA*, **29**, 363.
Yakovlev, D. G., Levenfish, K. P., and Shibanov, Yu. A. (1999) *Phys. Usp.* **42**, 737.
Zane, S., Turolla, R., Zampieri, L., Colpi, M., and Treves, A. (1995) *Astrophys. J.*, **451**, 739.