Evolution of Isolated Neutron Stars

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November 10, 2000

Abstract.
In this paper we briefly review our recent results on evolution and properties of isolated neutron stars (INSs) in the Galaxy.

As the first step we discuss stochastic period evolution of INSs. We briefly discuss how an INS's spin period evolves under influence of interaction with turbulized interstellar medium.

To investigate statistical properties of the INS population we calculate a *census* of INSs in our Galaxy. We infer a lower bound for the mean kick velocity of NSs, $< V > \sim$(200-300) $\mathrm{km\,s^{-1}}$. The same conclusion is reached for both a constant magnetic field ($B \sim 10^{12}$ G) and for a magnetic field decaying exponentially with a timescale $\sim 10^9$ yr. These results, moreover, constrain the fraction of low velocity NSs, which could have escaped pulsar statistics, to ∼few percents.

Then we show that for exponential field decay the range of minimum value of magnetic moment, μ_b: $\sim 10^{29.5} \geq \mu_b \geq 10^{28}\,\mathrm{G\,cm^3}$, and the characteristic decay time, t_d: $\sim 10^8 \geq t_d \geq 10^7$ yrs, can be excluded assuming the standard initial magnetic momentum, $\mu_0 = 10^{30}\,\mathrm{G\,cm^3}$, if accreting INSs are observed. For these parameters an INS would never reach the stage of accretion from the interstellar medium even for a low space velocity of the star and high density of the ambient plasma. The range of excluded parameters increases for lower values of μ_0.

It is shown that old accreting INSs become more abundant than young cooling INSs at X-ray fluxes below $\sim 10^{-13}$ erg cm^{-2} s^{-1}. We can predict that about one accreting INS per square degree should be observed at the *Chandra* and *Newton* flux limits of $\sim 10^{-16}$ erg cm^{-2} s^{-1}. The weak *ROSAT* sources, associated with INSs, can be young cooling objects, if the NSs birth rate in the solar vicinity during the last $\sim 10^6$ yr was much higher than inferred from radiopulsar observations.

Keywords: neutron stars, magnetic field, accretion

1. Introduction

Despite intensive observational campaigns, no irrefutable identification of an isolated accreting neutron star (NS) has been presented so far. Six soft sources have been found in ROSAT fields which are most probably associated to isolated radioquiet NSs. Their present X-ray and optical data however do not allow an unambiguous identification of the physical mechanism responsible for their emission. These sources can be powered either by accretion of the interstellar gas onto old ($\approx 10^{10}$ yr) NSs or by the release of internal energy in relatively young ($\approx 10^6$ yr) cooling NSs (see (Treves et al., 2000) for a recent review). The ROSAT candidates, although relatively bright (up to ≈ 1 cts s^{-1}), are intrinsically dim and their inferred luminosity ($L \approx 10^{31}$ erg s^{-1}) is near to that expected from either a close-by cooling NS or from an accreting NS among the most luminous. Their X-ray spectrum is soft and thermal, again as predicted for both accretors and coolers (Treves et al., 2000). Up to now only two optical counterparts have been identified (RXJ 1856, (Walter and Matthews, 1997); RXJ 0720, (Kulkarni and van Kerkwijk, 1998)) and in both cases an optical excess over the low-frequency tail of the black body X-ray spectrum has been reported. While detailed multiwavelength observations with next-generation instruments may indeed be the key for assessing the true nature of these sources, other, indirect, approaches may be used to discriminate in favor of one of the two scenarios proposed so far.

Since early 90^s, when in (Treves and Colpi, 1991) it was suggested to search for IANSs with ROSAT satellite, several investigations on INSs have been done (see for example (Madau and Blaes, 1994), (Manning et al., 1996), and (Treves et al., 2000) for a review). Here we present our recent results in that field.

Stochastic evolution of isolated neutron stars

One can distinguish four main stages of INS evolution: Ejector, Propeller, Accretor and Georotator (see (Lipunov, 1992) for more detailes). Destiny of an INS depends on its spin period, magnetic field, spatial velocity and properties of the interstellar medium (ISM). Schematically typical evolutionary paths can be shown on p-y diagram, where $y = \dot{M}/\mu^2$ – gravimagnetic parameter (Fig. 1).

An INS normally is born as Ejector. Then it spins down, and appear as Propeller. At last it can reach the stage of accretion, if its spatial velocity is low enough, or if the magnetic field is high.

As an INS evolves at the Accretor stage it more and more feels the influence of the turbulized nature of the ISM (Fig. 2). Initially isolated accreting NS spins down due to magnetic breaking, and the influence of accreted angular momentum is small. At last, at the stage of accretion, when the INS spun down enough, its rotational evolution is mainly governed by the turbulence, and the accreting angular moment fluctuates.

Observations of p and $\dot{p}$ of isolated accreting NSs can provide us not only with the information about INSs properties, but also about different properties of the ISM itself.

Figure 1. P-y diagram. Three evolutionary tracks are shown: 1 – evolution with constant field in constant medium. The NS spins down passing through different stages (Ejector, Propeller, Accretor); 2 – passing through a giant molecular cloud. The accretion rate is increased for some time, and the NS makes a loop on the diagram; 3 – evolution with field decay. The NS appears as Accretor due to fast field decay.

Neutron Star Census

We have investigated, (Popov et al., 2000a), how the present distribution of NSs in the different stages (Ejector, Propeller, Accretor and Georotator, see (Lipunov, 1992)) depends on the star mean velocity at birth (see Fig. 3). The fraction of Accretors was used to estimate the number of sources within 140 pc from the Sun which should have been

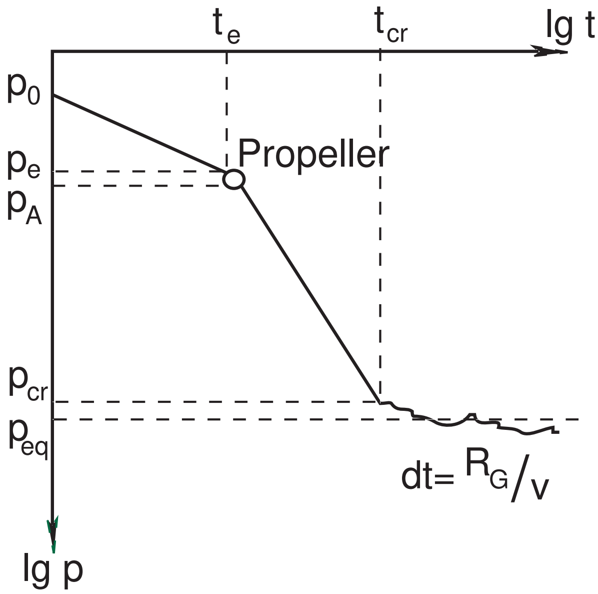

Figure 2. Evolution of an isolated NS in turbulized interstellar medium. After spin-down at the Ejector stage (spin-down up to $p = p_E$) and short Propeller stage (shown with a circle) the NS appears as accretor ($p > p_A$). Initialy magnetic breaking is more important than accretion of the angular momentum from the interstellar medium, and the NS constantly spins down. Then at $t = t_{cr}$ magnetic breaking and turbulent spin-up/spin-down become comparable, and spin period starts to fluctuate coming to some average ("equilibrium") value, p_{eq}. Typical timescale for fluctuations is $dt = R_G/v$, R_G – radius of gravitational capture, v – spatial velocity.

detected by ROSAT. Most recent analysis of ROSAT data indicate that no more than ~ 10 non–optically identified sources can be accreting old INSs. This implies that the average velocity of the INSs population at birth has to exceed $\sim 200\ \mathrm{km\,s^{-1}}$, a figure which is consistent with those derived from radio pulsars statistics. We have found that this lower limit on the mean kick velocity is substantially the same either for a constant or a decaying B–field, unless the decay timescale is shorter than $\sim 10^9$ yr. Since observable accretion–powered INSs are slow objects, our results exclude also the possibility that the present velocity distribution of NSs is richer in low–velocity objects with respect to a Maxwellian. The paucity of accreting INSs seem to lend further support in favor of NSs as fast objects.

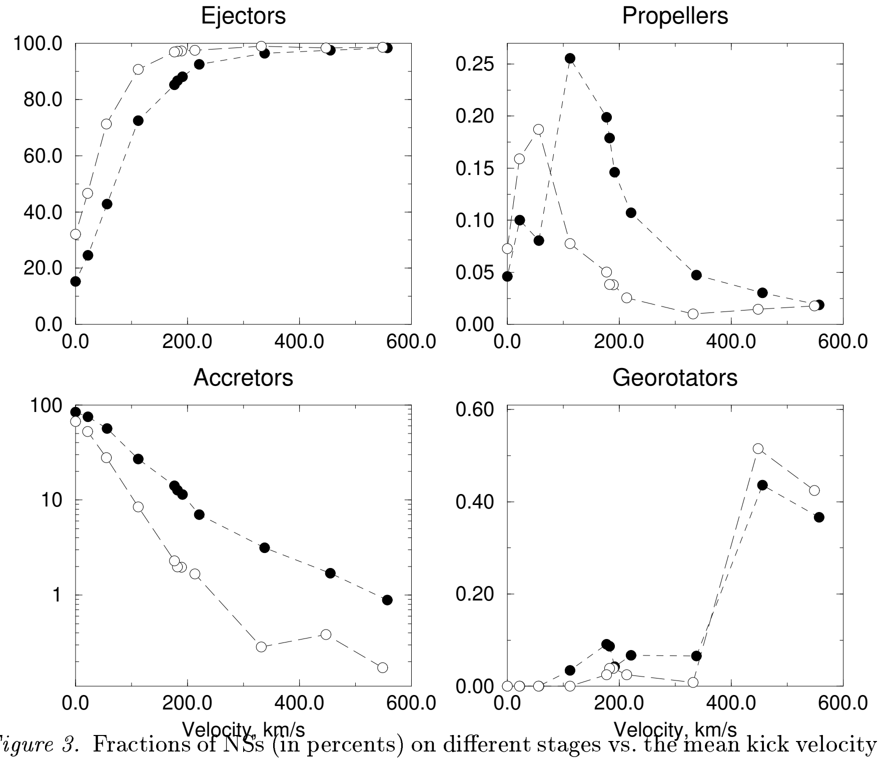

Figure 3. Fractions of NSs (in percents) on different stages vs. the mean kick velocity for two values of the magnetic moment: $\mu_{30} = 0.5$ (open circles) and $\mu_{30} = 1$ (filled circles). Typical statistical uncertainty for ejectors and accretors is $\sim$ 1-2%. Figures are plotted for constant magnetic field.

Magnetic Field Decay

Magnetic field decay can operate in INSs. Probably, some of observed ROSAT INS candidates represent such examples ((Konenkov and Popov, 1997), (Wang, 1997)) We tried to evaluate the region of parameters which is excluded for models of the exponential magnetic field decay in INSs using the possibility that some of ROSAT soft X-ray sources are indeed old AINSs.

In this section we follow the article (Popov and Prokhorov, 2000).

Here the field decay is assumed to have an exponential shape:

$$\mu = \mu_0 \cdot e^{-t/t_d}, \text{ for } \mu > \mu_b \tag{1}$$

where μ_0 is the initial magnetic moment ($\mu = \frac{1}{2} B_p R_{NS}^3$, here B_p is the polar magnetic field, R_{NS} is the NS radius), t_d is the characteristic time scale of the decay, and μ_b is the bottom value of the magnetic momentum which is reached at the time

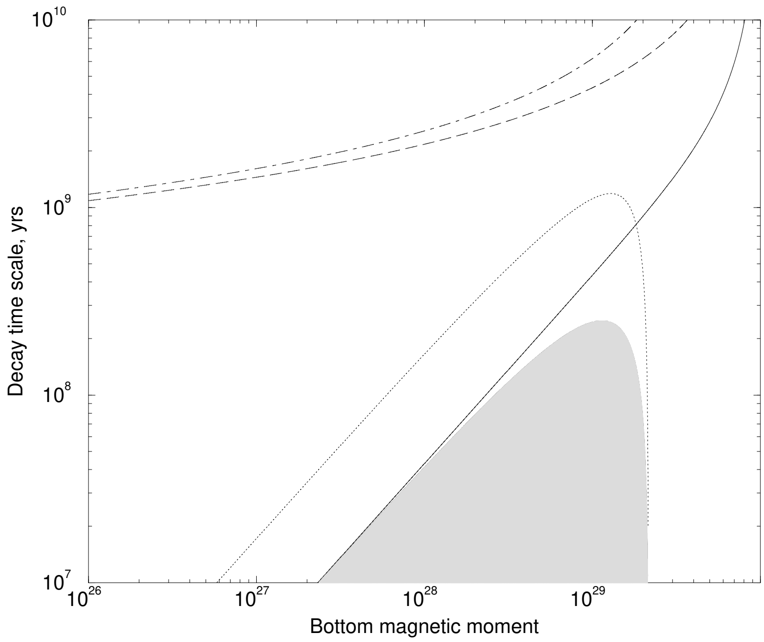

Figure 4. The characteristic time scale of the magnetic field decay, t_d, vs. bottom magnetic moment, μ_b. In the hatched region Ejector life time, t_E, is greater than 10^{10}yrs. The dashed line corresponds to $t_H = t_d \cdot \ln(\mu_0/\mu_b)$, where $t_H = 10^{10}$ years. The solid line corresponds to $p_E(\mu_b) = p(t = t_{cr})$, where $t_{cr} = t_d \cdot \ln(\mu_0/\mu_b)$. Both the lines and hatched region are plotted for $\mu_0 = 10^{30}\,\mathrm{G\,cm}^{-3}$. The dash-dotted line is the same as the dashed one, but for $\mu_0 = 5 \cdot 10^{29}\,\mathrm{G\,cm}^3$. The dotted line shows the border of the "forbidden" region for $\mu_0 = 5 \cdot 10^{29}\,\mathrm{G\,cm}^3$.

$$t_{cr} = t_d \cdot \ln\left(\frac{\mu_0}{\mu_b}\right) \quad (2)$$

and does not change after that.

The intermediate values of t_d ($\sim 10^7 - 10^8$ yrs) in combination with the intermediate values of μ_b ($\sim 10^{28} - 10^{29.5}\,\mathrm{G\,cm}^3$) for $\mu_0 = 10^{30}\,\mathrm{G\,cm}^3$ can be excluded for progenitors of isolated accreting NSs because NSs with such parameters would always remain on the Ejector stage and never pass to the accretion stage (see Fig. 4). Even if all modern candidates are not accreting objects, the possibility of limitations of magnetic field decay models based on future observations of isolated accreting NSs should be addressed.

For higher μ_0 NSs should reach the stage of Propeller (i.e. $p = p_E$, where p_E– is the Ejector period) even for $t_d < 10^8$ yrs, for weaker fields the "forbidden" region becomes wider. Critical period, p_E, corresponds to transition from the Propeller stage to the stage of Ejector, and is about 10-25 seconds for typical parameters. The results are dependent on the initial magnetic field, μ_0, the ISM density, n, and NSs velocity, V. So here different ideas can be investigated.

In fact the limits obtained above are even stronger than they could be in nature, i.e. "forbidden" regions can be wider, because we did not take into account that NSs can spend some significant time (in the case with field decay) at the propeller stage (the spin-down rate at this stage is very uncertain, see the list of formulae, for example, in (Lipunov and Popov, 1995) or (Lipunov, 1992)). The calculations of this effect for different models of non-exponential field decay were made separately (Popov and Prokhorov, 2001).

Note that there is another reason due to which a very fast decay down to small values of μ_b can also be excluded, because this would lead to a huge amount of accreting isolated NSs in drastic contrast with observations. This situation is similar to the "turn-off" of the magnetic field of an INS (i.e., quenching any magnetospheric effect on the accreting matter). So for any velocity and density distributions we should expect significantly more accreting isolated NSs than we know from ROSAT observations (of course, for high velocities X-ray sources will be very dim, but close NSs can be observed even for velocities ~ 100 km s^{-1}).

Log N – Log S distribution

In this section we briefly present our new results on INSs, (Popov et al., 2000b).

We compute and compare the $\log N - \log S$ distribution of both accreting and cooling NSs, to establish the relative contribution of the two populations to the observed number counts. Previous studies derived the $\log N - \log S$ distribution of accretors ((Treves and Colpi, 1991); (Madau and Blaes, 1994); (Manning et al., 1996)) assuming a NSs velocity distribution rich in slow stars ($v < 100$ km s^{-1}). More recent measurements of pulsar velocities (e.g. (Lyne and Lorimer, 1994)) and upper limits on the observed number of accretors in ROSAT surveys point, however, to a larger NS mean velocity (see (Treves et al., 2000) for a critical discussion). Recently in (Neühauser and Trümper, 1999) the authors compared the number count distribution of the ROSAT isolated NS candidates with those of accretors and coolers. In (Popov et al., 2000b) we address these issues in greater detail, also in the light of the latest contributions to the modeling of the evolution of Galactic NSs.

Our main results for AINSs are presented in Fig. 5 and Fig. 6.

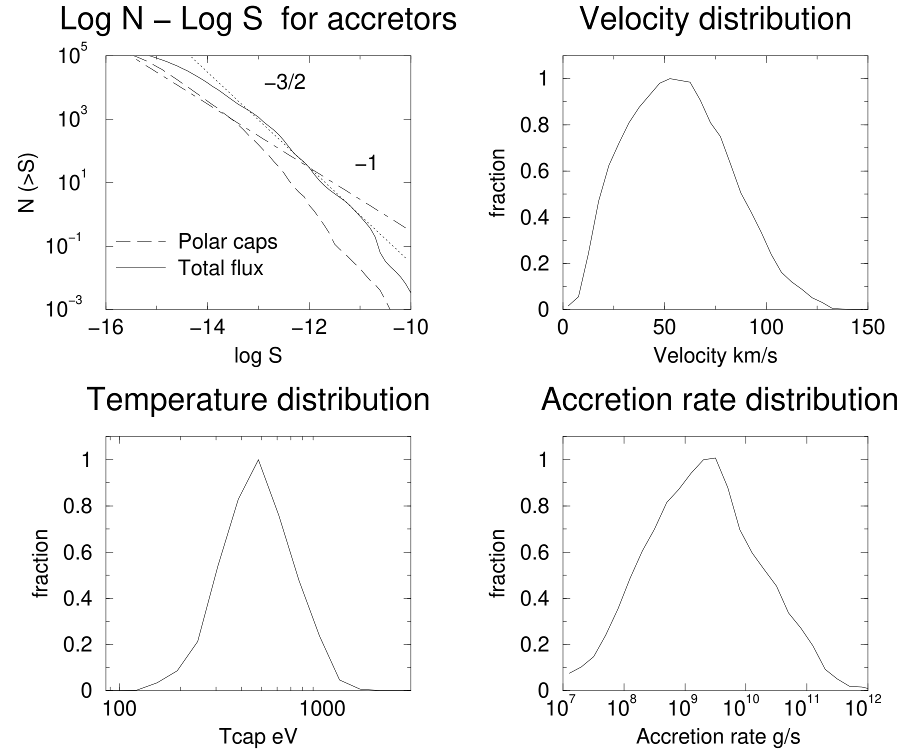

Figure 5. Upper left panel: the $\log N - \log S$ distribution for accretors within 5 kpc from the Sun. The two curves refer to total emission from the entire star surface and to polar cap emission in the range 0.5-2 keV; two straight lines with slopes -1 and -3/2 are also shown for comparison. From top right to bottom right: the velocity, effective temperature and accretion rate distributions of accretors; all distributions are normalized to their maximum value.

In Fig. 5 we show main parameters of accretors in our calculations: Log N – Log S distribution, distributions of velocity, accretion rate and temperature (for polar cap model).

In Fig. 6 we present joint Log N - Log S for accretors in our calculations, observed candidates, naive estimate from (Popov et al., 2000a), and our calculations for coolers in a simple model of local sources (Popov et al., 2000b).

Using "standard" assumptions on the velocity, spin period and magnetic field parameters, the accretion scenario can not explain the observed properties of the six ROSAT candidates.

A key result of our statistical analysis is that accretors should eventually become more abundant than coolers at fluxes below 10^{-13} erg cm^{-2} s^{-1}.

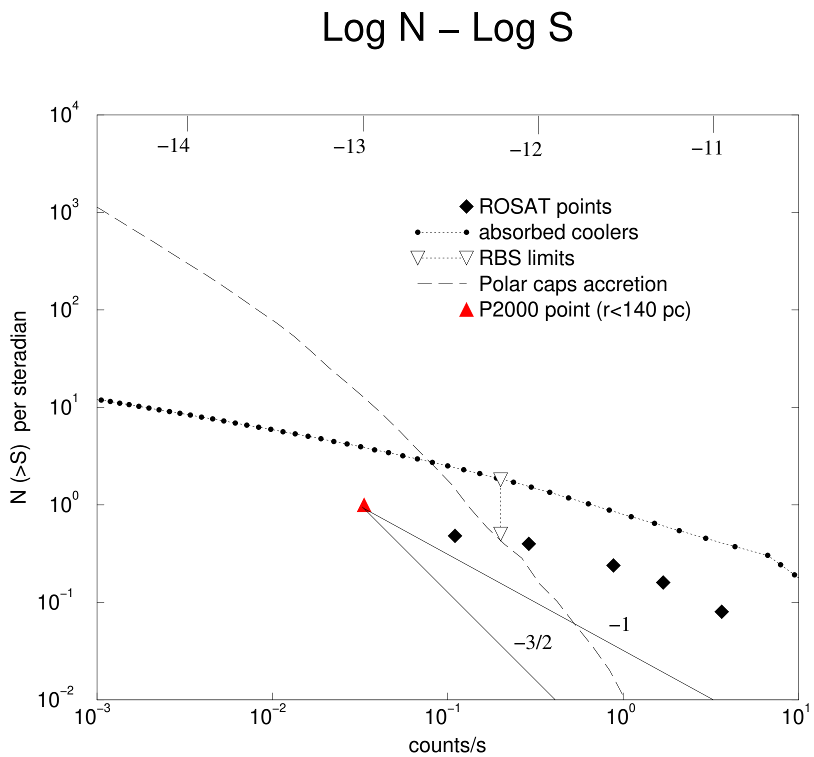

Figure 6. Comparison of the log N – log S distributions for accretors and coolers together with observational points, the naive log$N$ – log$S$ from P2000a and the ROSAT Bright Survey (RBS) limit. The scale on the top horizontal axes gives the flux in erg $cm^{-2}s^{-1}$.

Conclusions

INSs are now really *hot* objects. In many cases INSs can show different effects in the most "pure" form: without influence of huge accretion rate, for example.

We tried to show how these objects are related with models of magnetic field decay, and with recent and future X-ray observations.

Observed candidates propose "non-standard" properties of NSs. Future observations with XMM (Newton) and Chandra satellites can give more important facts.

INSs without usual radio pulsar activity (SGRs, AXPs, compact X-ray sources in SNRs, dim ROSAT candidates, Geminga, dim sources in globular clusters) together show "non-standard" or better say more complete picture of NS nature. Future investigations are strongly wanted.

Acknowledgements

I wish to thank my co-authors Monica Colpi, Vladimir Lipunov, Mikhail Prokhorov, Aldo Treves and Roberto Turolla. I also thank Organizers for their kind hospitality. The work was supported through the grant of Russian Foundation for Basic Research, Scientific Travel Center and INTAS.

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