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Isolated Neutron Stars in the Galaxy

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Abstract

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

As the first step 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 stars, which could have escaped pulsar statistics, to $\sim$few percents.

Then we show that 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.

Introduction

Despite intensive observational campaigns, no irrefutable identification of an isolated accreting neutron star (IANS) has been presented so far. Although six soft, weak sources, which are associated with isolated NSs, have been found in ROSAT fields, present X-ray and optical data do not allow an unambiguous determination 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) INSs or by the release of internal energy in relatively young ($\approx 10^{6}$ yr) cooling INSs (see [14] for recent review). 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 close to that expected from both close-by cooling and (most luminous) accreting INSs. Up to now only two optical counterparts have been possibly identified (RX J 1856-3754, [15]; RX J 0720-3125, [2]) 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 [13] it was suggested to search for IANSs with ROSAT satellite, several investigations on INSs have been done (see for exapmle [6], [7], and [14] for a review). Here we present our recent results in that field.

Neutron Star Census

We have investigated, [9], how the present distribution of NSs in the different stages (Ejector, Propeller, Accretor and Georotator, see [3]) depends on the star mean velocity at birth (see Fig. 1). The fraction of Accretors was used to estimate the number of sources within 140 pc from the Sun which should have been 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 ~ 200 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.

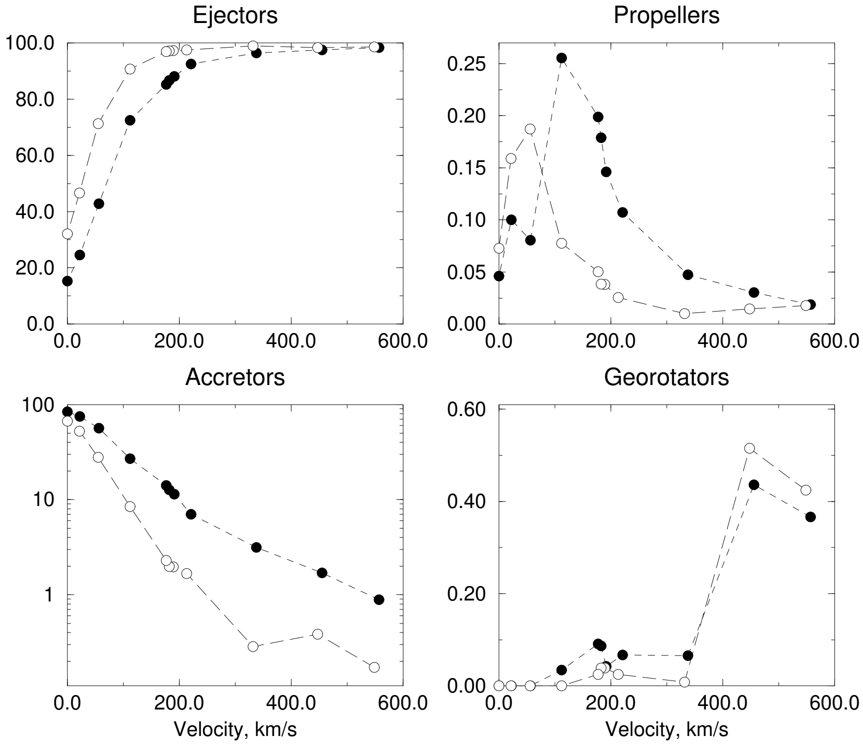

Figure 1: Fractions of NSs (in percents) on different stages vs. the mean kick velocity for $\mu_{30} = 0.5$ (open circles) and $\mu_{30} = 1$ (filled circles); typical statistical uncertainty for ejectors and accretors is $\sim$ 1-2%. Figures are plotted for constant magnetic field.

Magnetic Field Decay

Magnetic field decay can operate in INSs. Probably, some of observed ROSAT INS candidates represent such exapmples ([1], [16]) 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 [11].

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

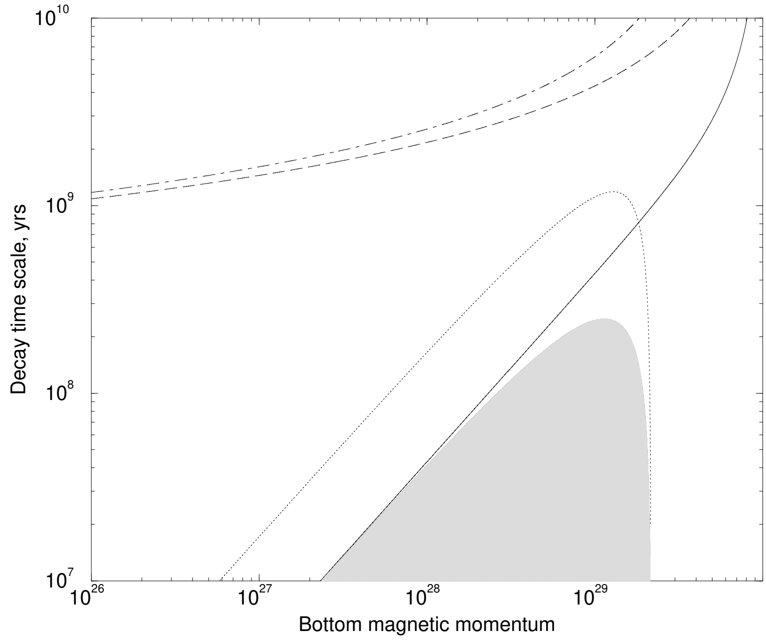

Figure 2: The characteristic time scale of the magnetic field decay, t_d, vs. bottom magnetic moment, μ_b. In the hatched region Ejector life time, t_E, is greater than 10^{10}yrs. The dashed line corresponds to $t_H = t_d \cdot \ln(\mu_0/\mu_b)$, where $t_H = 10^{10}$ years. The solid line corresponds 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 $\mu_0 = 5 \cdot 10^{29}\,\mathrm{G\,cm}^3$. See details in [11].

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

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. 2). 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 transision 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 [4] or [3]). The calculations of this effect for different models of non-exponential field decay were studied separately in [10].

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, [12].

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 ([13]; [6]; [7]) assuming a NSs velocity distribution rich in slow stars ($v < 100$ km s^{-1}). More recent measurements of pulsar velocities (e.g. [5]) and upper limits on the observed number of accretors in ROSAT surveys point, however, to a larger NS mean velocity (see [14] for a critical discussion). Recently Neühauser & Trümper ([8]) compared the number count distribution of the ROSAT isolated NS candidates with those of accretors and coolers. In [12] 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. 3.

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

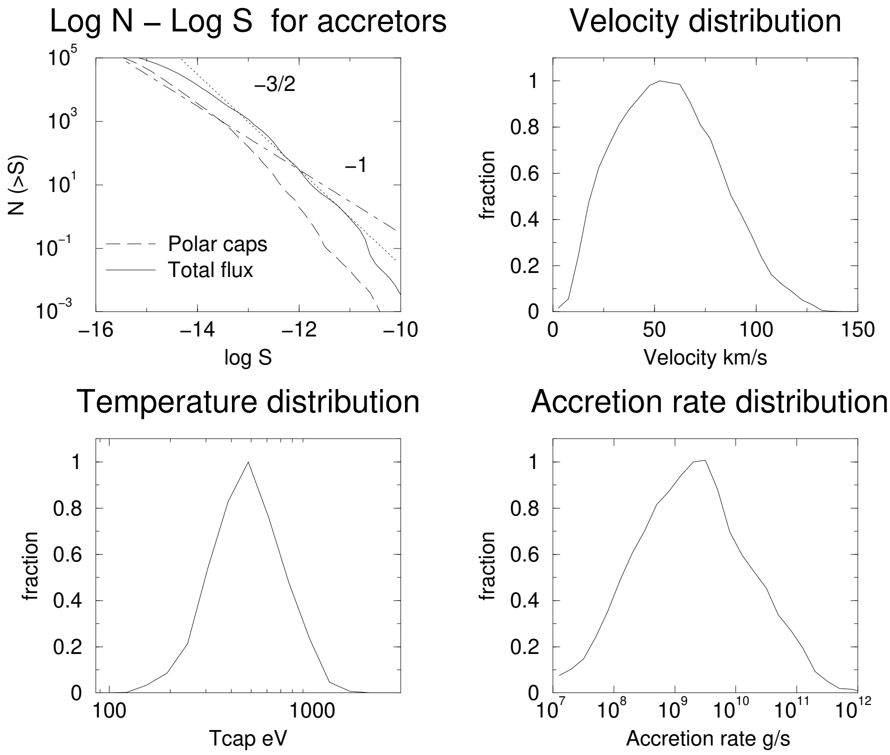

Figure 3: Upper left panel: the $\log N - \log S$ distribution for accretors within 5 kpc from the Sun. The two curves refer to total emission from the entire star surface and to polar cap emission in the range 0.5-2 keV; two straight lines with slopes -1 and -3/2 are also shown for comparison. From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

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}.

Conclusions

INSs are now a real *Hot Point in Astrophysics*. We tried to show how these objects are related with models of magnetic field decay, and with recent anf future X-ray observations.

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

Acknowledgments

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