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#### Population synthesis of old neutron stars in the galaxy

S. B. Popov<sup>a</sup>; M. Colpi<sup>b</sup>; A. Treves<sup>c</sup>; R. Turolla<sup>d</sup>; V. M. Lipunov<sup>ae</sup>; M. E. Prokhorov<sup>a</sup>

<sup>a</sup> Sternberg Astronomical Institute, Moscow, Russia

<sup>b</sup> Department of Physics, University of Milan, Milan, Italy

<sup>c</sup> Dipartimento di Scienze, University dell'Insubria, Como, Italy

<sup>d</sup> Department of Physics, University of Padova, Padova, Italy

<sup>e</sup> Department of Physics, Moscow State University, Moscow, Russia

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## POPULATION SYNTHESIS OF OLD NEUTRON STARS IN THE GALAXY

S. B. POPOV,<sup>1</sup> M. COLPI,<sup>2</sup> A. TREVES,<sup>3</sup> R. TUROLLA,<sup>4</sup>  
V. M. LIPUNOV,<sup>1,5</sup> and M. E. PROKHOROV<sup>1</sup>

<sup>1</sup>*Sternberg Astronomical Institute,  
Universitetskii Pr. 13, 119899, Moscow, Russia, E-mail: polar@xray.sai.msu.ru*

<sup>2</sup>*Department of Physics, University of Milan,  
Via Celoria 16, 20133 Milan, Italy, E-mail: monica@pccolpi.uni.mi.astro.it*

<sup>3</sup>*Dipartimento di Scienze University dell'Insubria,  
Via Lucini 3, 22100, Como, Italy, E-mail: treves@mi.infn.it*

<sup>4</sup>*Department of Physics, University of Padova,  
Via Marzolo 8, 35131 Padova, Italy, E-mail: roberto.turolla@pd.infn.it*

<sup>5</sup>*Department of Physics, Moscow State University  
119899 Moscow, Russia, E-mail: lipunov@sai.msu.ru*

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The paucity of old isolated accreting neutron stars in ROSAT observations is used to derive a lower limit on the mean velocity of neutron stars at birth. The secular evolution of the population is simulated following the paths of a statistical sample of stars for different values of the initial kick velocity, drawn from an isotropic Gaussian distribution with mean velocity  $0 \leq \langle V \rangle \leq 550 \text{ km s}^{-1}$ . The spin-down induced by dipole losses and the interaction with the ambient medium is tracked together with the dynamical evolution in the Galactic potential, allowing for the determination of the fraction of stars which are, at present, in each of the four possible stages: ejector, propeller, accretor, and georotator. Taking from the ROSAT All Sky Survey an upper limit of  $\sim 10$  accreting neutron stars within  $\sim 140 \text{ pc}$  from the Sun, we infer a lower bound for the mean kick velocity,  $\langle V \rangle \geq 200\text{--}300 \text{ km s}^{-1}$ . The same conclusion is reached for both a constant ( $B \sim 10^{12} \text{ G}$ ) and a magnetic field decaying exponentially with a timescale  $\sim 10^9 \text{ yr}$ . Present results, moreover, constrain the fraction of low-velocity stars, which could have escaped pulsar statistics, to  $\leq 1\%$ .

KEY WORDS Neutron stars, accretion, X-ray sources

### 1 INTRODUCTION

Isolated neutron stars (NSs) are expected to be as many as  $10^8\text{--}10^9$ , a non-negligible fraction of the total stellar content of the Galaxy. The number of observed radio pulsars is now  $\geq 1000$ . Since the pulsar lifetime is  $\sim 10^7 \text{ yr}$ , this implies that the bulk of the NS population, mainly formed of old objects, remains undetected as yet. Despite intensive searches at all wavelengths, only a few (putative) isolated

NSs which are not radio pulsars (or soft  $\gamma$ -repeaters) have been recently discovered in the X-rays with ROSAT (Walter *et al.*, 1996; Haberi *et al.*, 1998; Neuhäuser and Trümper, 1999). The extreme X-ray to optical flux ratio ( $> 10^3$ ) makes the NS option rather robust; the exact nature of their emission is still controversial. Up to now, two main possibilities have been suggested: either relatively young NSs radiating away their residual internal energy or much aged NSs accreting the interstellar gas. Both options have advantages and drawbacks. Standard cooling atmosphere models fail to predict in a natural way the spectrum of the best studied object, RX J1856-3754. If the Bondi–Hoyle scenario applies, accretion is reduced for increasing star velocity and for  $v > 20 \text{ km s}^{-1}$  it fails to produce the luminosities inferred from ROSAT data. Meanwhile, we feel that a more thorough analysis of the statistical properties of NSs is of interest and can be useful in providing indirect evidence in favour of or against the accretion scenario.

As discussed by Lipunov (1992), isolated NSs can be classified into four main types: ejectors, propellers, accretors and georotators. In ejectors the relativistic outflowing momentum flux is always larger than the ram pressure of the surrounding material so they never accrete and are either active radio pulsars or dead pulsars, still spun down by dipole losses. In propellers the incoming matter can penetrate down to the Alfvén radius,  $R_A$ , but no further because of the centrifugal barrier, and, although stationary inflow cannot occur, the piling up of the material at the Alfvén radius may give rise to (supposedly short) episodes of accretion (Trevés *et al.*, 1993; Popov, 1994). Steady accretion is also impossible in georotators where (similarly to the Earth) the Alfvén radius exceeds the accretion radius, so that magnetic pressure dominates everywhere over the gravitational pull. It is the combination of the star period, magnetic field and velocity that decides which type a given isolated NS belongs to and, since  $P$ ,  $B$  and  $V$  change during the star evolution, a NS can go through different stages in its lifetime.

The dynamical evolution of NSs in the Galactic potential was studied by several authors (see e.g. Madau and Blaes, 1994; Zane *et al.*, 1995). Little attention was paid to the NSs magneto-rotational evolution. Recently, this issue was discussed in some detail by Livio *et al.* (1998) and Colpi *et al.* (1998).

The goal of this investigation is to consider these two issues simultaneously, coupling the dynamical and the magneto-rotational evolution for the isolated NS population.

The possibility that the low-velocity tail is underpopulated with respect to what was previously assumed should be seriously taken into account. It is our aim to revise the estimates on the number of old accreting neutron stars in the Galaxy in the light of these new data, in an attempt to reconcile theoretical predictions with present ROSAT limits (Neuhäuser and Trümper 1999).

## 2 THE MODEL

In this section we summarize the main hypothesis introduced to track the evolution of single stars and describe briefly the technique used to explore their statistical

properties, referring to Popov and Prokhorov (1998) for details on spatial evolution calculations and to Konenkov and Popov (1997) and Lipunov and Popov (1995) for details of magneto-rotational evolution.

### 2.1 Dynamical Evolution

The dynamical evolution of each single star in the Galactic potential is followed solving its equations of motion. The potential is taken in the form proposed by Miyamoto and Nagai (1975).

The period evolution depends on both the star velocity and the local density of the interstellar medium; any attempt to investigate the statistical properties of the NS population should incorporate a detailed model of the ISM geography. Unfortunately the distribution of molecular and atomic hydrogen in the Galaxy is highly inhomogeneous. Here we use the analytical distributions from Bochkarev (1992) and Zane *et al.* (1995). Within a region of  $\sim 140$  pc around the Sun, the ISM is underdense, and we take  $n = 0.07 \text{ cm}^{-3}$ .

In our model we assume that the NS birthrate is constant in time and proportional in magnitude to the square of the local gas density.

Neutron stars at birth have a circular velocity determined by the Galactic potential. Superposed on this ordered motion, a kick velocity is imparted in a random direction. We use here an isotropic Gaussian distribution with dispersion  $\sigma_V$ , simply as a means to model the true pulsar distribution at birth (see e.g. Cordes, 1998). The mean velocity  $\langle V \rangle = (8/\pi)^{1/2} \sigma_V$  is varied in the interval 0–550  $\text{km s}^{-1}$ .

### 2.2 Accretion Physics and Period Evolution

The accretion rate was calculated according to the Bondi formula

$$\dot{M} = \frac{2\pi(GM)^2 m_p n(R, Z)}{(V^2 + V_s^2)^{3/2}} \simeq 10^{11} n v_{10}^{-3} \text{ g s}^{-1}, \quad (1)$$

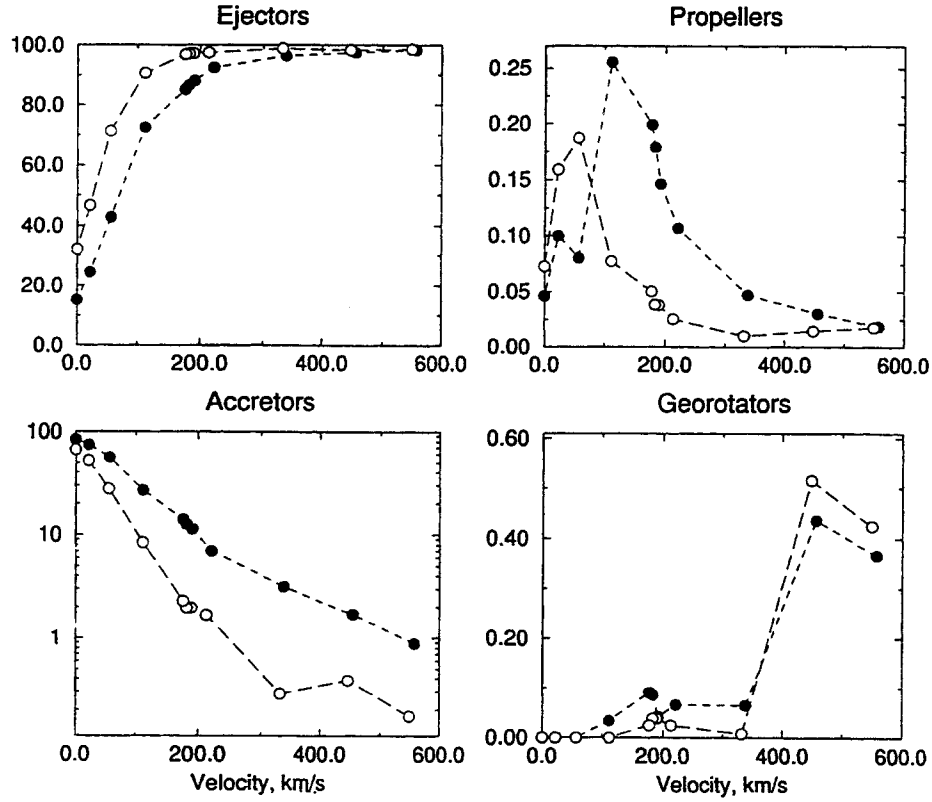
where  $m_p$  is the proton mass, the sound speed  $V_s$  is always  $10 \text{ km s}^{-1}$  and  $v_{10} = (V^2 + V_s^2)^{1/2}$  in units of  $10 \text{ km s}^{-1}$ .  $M$  denote the NS mass which we take equal to  $1.4M_\odot$  for all stars. The NS radius was taken to be  $10 \text{ km}$ .

All neutron stars are assumed to be born with a period  $P(0) = 0.02 \text{ s}$ , and a magnetic moment either  $\mu_{30} = 1$  or  $\mu_{30} = 0.5$ , where  $\mu_{30} = \mu/10^{30} \text{ G cm}^3$ .

In the ejector phase the energy losses are due to magnetic dipole radiation. When the gravitational energy density of the incoming interstellar gas exceeds the outward momentum flux at the accretion radius,  $R_{ac} \simeq 2GM/v^2$ , matter starts to fall in. This happens when the period reaches the critical value

$$R_E(E \rightarrow P) \simeq 10 \mu_{30}^{1/2} n^{-1/4} v_{10}^{1/2} \text{ s}. \quad (2)$$

When  $P > P_E(E \rightarrow P)$  the NS is in the propeller phase, rotational energy is lost and the period keeps increasing at a rate taken from Shakura (1975).



**Figure 1** Fractions of NSs in the different stages vs. the mean kick velocity for  $\mu_{30} = 0.5$  (opaque circles) and  $\mu_{30} = 1$  (filled circles); typical statistical uncertainty for ejectors and accretors is  $\sim 1$ –2%.

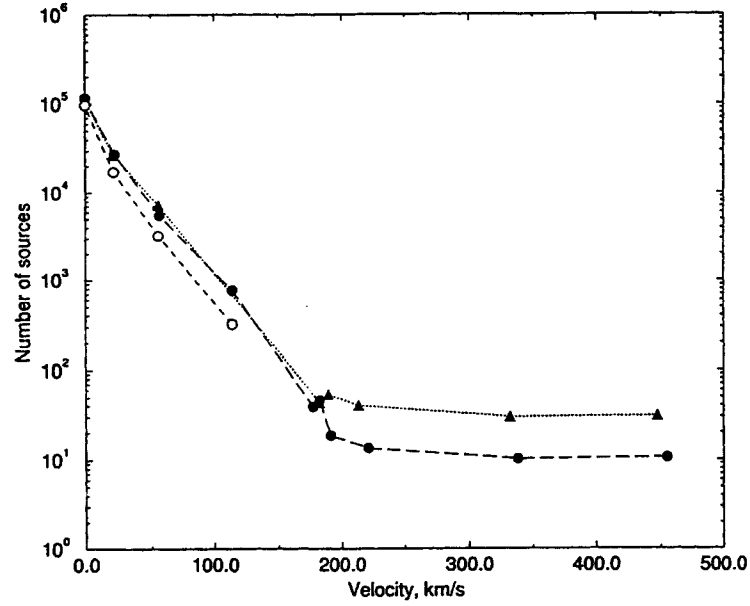
As the star moves through the inhomogeneous ISM a transition from the propeller back to the ejector phase may occur if the period attains the critical value

$$P_e(P \rightarrow E) \simeq 3\mu_{30}^{4/5} v_{10}^{6/7} n^{-2/7} \text{ s.} \quad (3)$$

Note that the transitions  $P \rightarrow E$  and  $E \rightarrow P$  are not symmetric as first discussed by Shvartsman in the early 1970s.

Accretion onto the star surface occurs when the corotation radius  $R_{co} = (GM P^2 / 4\pi^2)^{1/3}$  becomes larger than the Alfvén radius (and  $R_A < R_{ac}$ , see below). This implies that braking torques have increased the period up to

$$P_A(P \rightarrow A) \simeq 420\mu_{30}^{6/7} n^{-3/7} v_{10}^{9/7} \text{ s.} \quad (4)$$



**Figure 2** Number of accreting NSs in the Solar vicinity for a constant ( $\mu_{30} = 1$ , filled circles;  $\mu_{30} = 0.5$ , opened circles) and decaying field ( $t_d = 2.2 \times 10^9$  yrs, triangles).

As soon as the NS enters the accretor phase, torques produced by stochastic angular momentum exchanges in the ISM slow down the star rotation at the equilibrium period

$$P_{\text{eq}} = 2.6 \times 10^3 v_{(t)10}^{-2/3} \mu_{30}^{2/3} n^{-2/3} v_{10}^{13/3} \text{ s}, \quad (5)$$

where  $v_{(t)}$  is the turbulent velocity of the ISM (Lipunov and Popov, 1995; Konenkov and Popov, 1997).

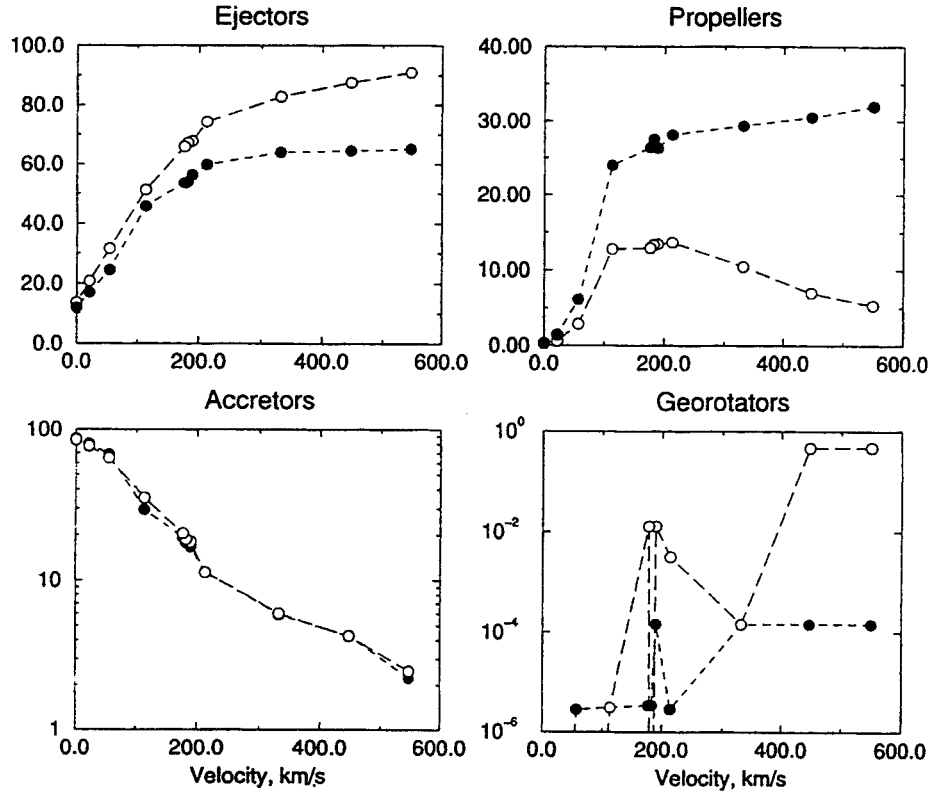
At the very low accretion rates expected for fast isolated NSs, it could be that the Alfvén radius is larger than the accretion radius. The condition  $R_A < R_{\text{ac}}$  translates into a limit for the star velocity

$$v < 410 n^{1/10} \mu_{30}^{-1/5} \text{ km s}^{-1}. \quad (6)$$

### 3 RESULTS AND DISCUSSION

#### 3.1 The NS Census for a Non-Decaying Field

We consider two values for the magnetic dipole moment ( $\mu_{30} = 0.5$  and  $\mu_{30} = 1$ ) for the constant NS magnetic field. The present fraction of NSs in the ejector and accretor stages as a function of the mean kick velocity is shown in Figure 1.



**Figure 3** Fractions of NSs in the different stages vs. the average kick velocity for a decaying field with an e-folding time  $t_d = 2.2 \times 10^9$  yrs (opaque circles) and  $t_d = 1.1 \times 10^9$  yrs (filled circles).

In order to compare the expected number of accreting ONSs with the ROSAT All Sky Survey (RASS) results, we evaluated the number of those ONSs, within 140 pc from the Sun, producing an unabsorbed flux of  $10^{-13}$  erg cm $^{-2}$  s $^{-2}$  or higher at energies  $\sim 100$  eV. The results are illustrated in Figure 2. The main result is that for mean velocities below 200 km s $^{-1}$  the number of ONSs with a flux above the RASS detection limit would exceed 10. Most recent analysis on the number of isolated NSs in the RASS (Neuhäuser and Trümper, 1999) indicate that the upper limit is below 10.

Here, and in the following the total number of Galactic NSs was assumed to be  $10^9$ . A total number  $\sim 10^9$  appears to be consistent with the nucleosynthesis and chemical evolution of the Galaxy, while  $10^8$  is derived from radio pulsar observations. It is uncertain if all NSs experience an active radio pulsar phase, due to low initial magnetic fields or long periods, or to the fall-back in the aftermath of the supernova explosion. There is a serious possibility that the total number of NSs derived from radio pulsar statistics is only a lower limit. An important aspect is that our results

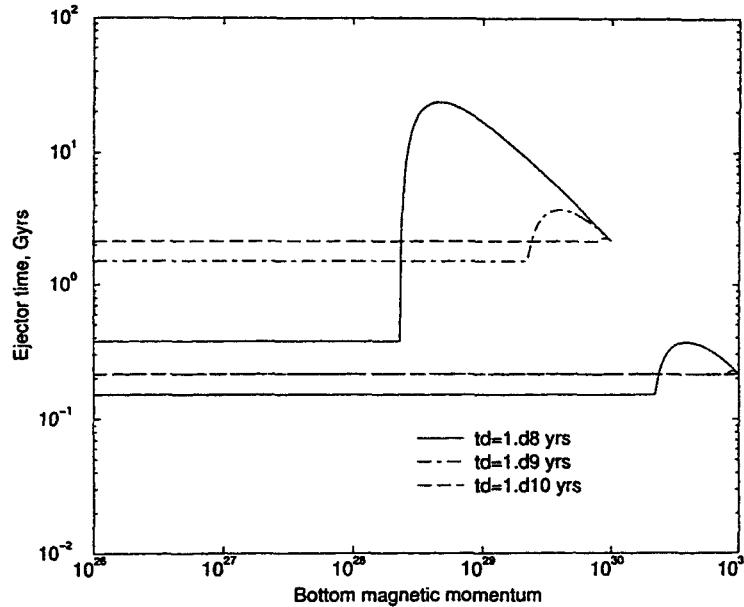


Figure 4 Ejector time vs. bottom magnetic momentum for two values of initial magnetic momentum and different scales of decay,  $t_d$ ,  $10^8$ ,  $10^9$ , and  $10^{10}$  years.

exclude the possible presence of a consistent low-velocity population at birth, which exceeds that contained in the Gaussian with  $\langle V \rangle > 200 \text{ km s}^{-1}$  ( $\sim 1\%$  for  $\langle V \rangle < 70 \text{ km s}^{-1}$ ).

### 3.2 The NS Census for a Decaying Field

We refer here only to a very simplified picture of the field decay in which  $B(t) = B(0) \exp(-t/t_d)$ . Calculations have been performed for  $t_d = 1.1 \times 10^9 \text{ yr}$ ,  $t_d = 2.2 \times 10^9 \text{ yr}$  and  $\mu_{30}(0) = 1$ . Results are shown in Figure 3.

For some values of  $t_d$  and bottom field most of the NS can stay at the ejector stage, and numbers of accretors and propellers would not be increased. We show this analytical estimate graphically in Figure 4, where the ejector time,  $T_E$ , is plotted vs. bottom magnetic momentum for constant velocity and ISM density ( $n = 1 \text{ cm}^{-3}$ ,  $v = 10 \text{ km s}^{-1}$ ), different  $t_d$  and two values of the initial magnetic momentum,  $10^{30}$  and  $10^{31} \text{ G cm}^3$  (see details in Popov and Prokhorov, 2000).

Summarizing, we can conclude that, although both the initial distribution and the subsequent evolution of the magnetic field strongly influences the NS census and should be accounted for, the lower bound on the average kick derived from ROSAT surveys is not very sensitive to  $B$ , at least for not too extreme values of  $t_d$  and  $\mu(0)$ , within this model.



#### 4 CONCLUSIONS

In this paper we have investigated how the present distribution of neutron stars in the different stages (ejector, propeller, accretor and georotator) depends on the star mean velocity at birth. On the basis of a total of  $\sim 10^9$  NSs, 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  $\sim 10$  non-optically identified sources can be accreting ONSs. This implies that the average velocity of the NS population at birth has to exceed  $\sim 200 \text{ km s}^{-1}$ , a figure which is consistent with those derived from radio pulsar 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 ONSs 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 ONSs seem therefore to lend further support in favour of neutron stars as very fast objects.

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