The Neutron Star Census

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ABSTRACT

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 $0 \leq \langle V \rangle \leq 550$ 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 ~ 10 accreting neutron stars within ~ 140 pc from the Sun, we infer a lower bound for the mean kick velocity, $\langle V \rangle \gtrsim 200 - 300$ km s^{-1}, corresponding to a velocity dispersion $\sigma_V \gtrsim 125 - 190$ km s^{-1}. The same conclusion is reached for both a constant ($B \sim 10^{12}$ G) and a magnetic field decaying exponentially with a timescale $\sim 10^9$ yr. Such high velocities are consistent with those derived from radio pulsar observations. Present results, moreover, constrain the fraction of low velocity stars, which could have escaped pulsar statistics, to $\lesssim 1\%$.

Subject headings: Accretion, accretion disks — stars: neutron — X–rays: stars

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1. Introduction

Isolated neutron stars (NSs) are expected to be as many as 10^8–10^9, a non–negligible fraction ($\sim 1\%$) of the total stellar content of the Galaxy. The number of observed radio pulsars is now $\sim$ 1,000. Since the pulsar lifetime is $\approx 10^7$ 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 γ repeaters) have been recently discovered in the X–rays with ROSAT (Walter et al. 1996; Haberl et al. 1996; Haberl et al. 1998; Neühauser & Trümper 1999; Schwope et al. 1999). All these sources emit a thermal spectrum at $\approx$ 100 eV and the derived column densities place them at relatively close distances ($\lesssim$ 140 pc) with luminosities $L \sim 10^{30}$–10^{31} ergs^{-1}. For two of them (RX J1856-3754, RX J0720-3125), extremely faint optical counterparts ($m_V \sim 26$) have been firmly established (Walter & Matthews 1997; Kulkarni & van Kerkwijk 1998; Motch & Haberl 1998) while for other sources plate searches placed limits down to $m_V \gtrsim 26$. Although 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. Cooling atmosphere models fail to predict in a natural way the optical excess observed in the best studied object, RX J1856-3754, while this seems be a distinctive feature of accreting atmospheres (Zane, Turolla & Treves 1999). On the other hand, at least if the Bondi–Hoyle scenario applies, accretion is reduced for increasing star velocity and for $v > 20$ km s^{-1} it fails to produce the luminosities inferred from ROSAT data. When they become available, proper motion measurements for some of the five isolated NS candidates detected so far will prove decisive in assessing the true nature of these sources. 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 favor 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 Alfven radius but no further because of the centrifugal barrier, and, although stationary inflow can not occur, the piling up of the material at the Alfven radius may give rise to (supposedly short) episodes of accretion (Treves, Colpi & Lipunov 1993 ; Popov 1994). Steady accretion is also impossible in Georotators where (similarly to the Earth) the Alfven 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 both P, B and V change during the star evolution, a NS can go through different stages in its lifetime. This argument shows that, at variance with what was assumed in earlier investigations (Treves & Colpi 1991; Blaes & Madau 1993; Zane et al. 1995) stationary accretion onto an isolated old NS (ONS hereafter) depends crucially on its rotational period and magnetic field.

The dynamical evolution of NSs in the Galactic potential was studied by several authors (Paczyński 1990; Blaes & Rajagopal 1991; Blaes & Madau 1993; Madau & Blaes 1994; Zane et al. 1995) who computed the present velocity distribution, one of the key parameters governing accretion. Until now, however, little attention was paid to the NSs magneto–rotational evolution. Only recently, this issue was discussed in some detail by Livio Xu & Frank (1998) and Colpi et al. (1998), who found that, for a given velocity distribution, the number of accreting sources depends strongly on the extent of the magnetic field decay.

Goal of this investigation is to consider these two issues simultaneously, coupling the dynamical and the magneto–rotational evolution for the isolated NS population. In particular, we explore the effects induced on the current census of NSs by varying the mean value of the kick velocity. In earlier investigations (Treves & Colpi 1991; Blaes & Madau 1993; Zane et al. 1995), the velocity distribution at birth was assumed either Gaussian with a mean velocity (inferred on the basis of existent data, Narayan & Ostriker 1990) of ~ 70 km s^{-1}, or skewed towards higher velocities (~ 200 km s^{-1}) but still rich in slow stars (Paczyński 1990). In the last few years however, proper motion studies and revised distance estimates of pulsar subpopulations revealed that young neutron stars have high mean velocities, ~ 400 km s^{-1} according to the original suggestion by Lyne & Lorimer (1994) or ~ 200 km s^{-1} on the basis of the more recent analyses by Hansen & Phinney (1997), Cordes & Chernoff (1997) and Cordes & Chernoff (1998). Although little is known about the low–velocity tail of the distribution and it is still unclear if pulsars are really representative of the entire NS population (Hartman 1997; Hartman et al. 1997), 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, and in the solar vicinity in particular, in the light of these new data, in the attempt to reconcile theoretical predictions with present ROSAT limits (Neühauser & Trümper 1999). This is of potential importance as it may indirectly unveil how the long term evolution of key parameters, such as the magnetic field, the period, the velocity distribution and the star formation rate relate to the properties of neutron stars at birth and to their interaction with the Galactic environment.

2. The Model

In this section we summarize the main hypothesis introduced to track the evolution of single stars and describe shortly the technique used to explore their statistical properties, referring to Popov & Prokhorov (1998), Popov & Prokhorov (1999) for details on spatial evolution calculations.

2.1. Dynamical evolution

The dynamical evolution of each single star in the Galactic potential is followed solving its equations of motion. The potential, proposed by Miyamoto & Nagai (1975) and adopted later by Paczýnski (1990), is given by the superposition of a spherical halo and of two flattened bulge/disk components. In Galactocentric cylindrical coordinates R, Z, $r=\sqrt{R^2+Z^2}$, they are expressed as

$$\Phi_H(R,Z) = -\frac{GM_C}{r_C}\left[\frac{1}{2}\ln\left(1+\frac{r^2}{r_C^2}\right)+\frac{r_C}{r}\tan^{-1}\left(\frac{r}{r_C}\right)\right] \qquad (1)$$

and

$$\Phi_i(R,Z) = -\frac{GM_i}{\sqrt{R^2+[a_i+(Z^2+b_i^2)^{1/2}]^2}} \qquad (2)$$

where the index i stands both for B (bulge) and D (disk). The values of the parameters appearing in equations (1) and (2) are summarized in table 1.

In their motion through the Galaxy, NSs interact with the interstellar medium (ISM) when (and if) they enter the Propeller or the Accretor phase. In these two stages the accreting material affects significantly the star spin because braking torques arise (see §2.3). Since 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 and only an averaged description is possible. Here we use the analytical distributions from Bochkarev (1992) and Zane et al. (1995) . Denoting with n_{HI} and n_{H_2} the neutral and molecular hydrogen number density, the total proton density is given by

$$n(R,Z) = n_{HI} + 2n_{H_2}. \qquad (3)$$

The molecular hydrogen distribution is approximated as

$$n_{H_2}(R,Z) = n_2(R)\,\exp\left[\frac{-Z^2}{2\cdot(70\mathrm{pc})^2}\right] \qquad (4)$$

where $n_2(R)$ is tabulated in Bochkarev (1992). The map of atomic hydrogen is more complex and for $R \le 3.4$ kpc we assume

$$n_{HI} = n_0(R)\exp\left[\frac{-Z^2}{2\cdot(140\,\mathrm{pc})^2}\left(\frac{R}{2\,\mathrm{kpc}}\right)^2\right]. \qquad (5)$$

The preceding expression becomes inaccurate below ~ 1 kpc, where the gas distribution is dominated by a rotating ring and dense clouds. However, since we do not calculate the evolution of NSs born in the central 2 kpc, this is not going to be of any relevance (see Zane et al. 1996a for a discussion of the diffuse X–ray emission from accreting NSs in the Galactic Center). The density of cold and warm HI at $3.4\,\mathrm{kpc} \le R \le 8.5\,\mathrm{kpc}$ can be fitted by

$$n_{HI} = 0.345\,\exp\left[\frac{-Z^2}{2\cdot(212\,\mathrm{pc})^2}\right] +$$

Table 1

Parameters for the various contributions to the Galactic potential

Halo	Bulge	Disk
$r_C = 6.0$ kpc	$a_B = 0.0$ kpc	$a_D = 3.7$ kpc
–	$b_B = 277$ pc	$b_D = 200$ pc
$M_C = 5.0 \times 10^{10}\, M_\odot$	$M_B = 1.1 \times 10^{10}\, M_\odot$	$M_D = 8.1 \times 10^{10}\, M_\odot$

$$0.107 \exp\left[\frac{-Z^2}{2\cdot(530\,\mathrm{pc})^2}\right] + 0.064 \exp\left[\frac{-Z}{403\,\mathrm{pc}}\right]. \quad (6)$$

while at radii larger than 8.5 kpc we use

$$n_{HI} = n_3(R) \exp\left[\frac{-Z^2}{2\cdot(530\,\mathrm{pc})^2}\left(\frac{R}{8.5\,\mathrm{kpc}}\right)^2\right] \quad (7)$$

where $n_0(R)$ and $n_3(R)$ are again taken from Bochkarev (1992). The total hydrogen density distribution used in our computations is shown in figure 1; the density in the galactic plane varies by more than one order of magnitude, ranging from $0.1\,\mathrm{cm}^{-3}$ to $4.3\,\mathrm{cm}^{-3}$. Within a region of ~ 140 pc around the Sun, the ISM is underdense, and we take $n = 0.07$ cm^{-3} (see Zane et al. 1996a).

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 (see for example Cox 1983; Firmani & Tutukov 1994). This implies that NSs are preferentially produced in the molecular ring region and migrate through the Galaxy during their evolution, due to the large kick velocities acquired at birth. Stars are assumed to be born in the Galactic plane ($Z = 0$) and in the range $2\,\mathrm{kpc} < R < 16\,\mathrm{kpc}$; this limitation has no major influence on the results, and on the number of sources found in the solar vicinity in particular. In the present investigation all effects of NSs born in binary systems (see, e.g., Iben & Tutukov 1998) has been neglected.

Neutron stars at birth have a circular velocity determined by the Galactic potential. Superposed to this ordered motion a kick velocity is imparted in a random direction. The exact form of the kick distribution is still uncertain (see, e.g., Lipunov et al. 1996a; Iben & Tutukov 1998; Belczyński & Bulik 1999). Here we use an isotropic Gaussian distribution with dispersion σ_V, simply as a mean 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 km s^{-1}. The velocity dispersion of the NS progenitors, $\sim$ 20 km s^{-1}, has been neglected and runs with $\langle V\rangle$ of this order mimic a NSs population with zero mean kick velocity at birth.

For each star the dynamical evolution has been followed up to present time. The evolution of the spin period P (as described in §2.3) is also computed, keeping track of the different stages the neutron star experiences (Ejector, Propeller, etc.). A number of representative evolutionary paths have been calculated, placing the stars on a uniform spatial grid with a randomly orientated kick drawn from the specified Gaussian distribution. Each evolutionary track is statistically independent and in order to mimic continuous star formation in the galactic plane at various locations (the n^2 density law), a single track is sampled in time and repeatedly used, shifting ahead the starting time. Tracks beginning from a denser region have accordingly a higher statistical weight. In the time sampling procedure, a single track gives a contribution to the statistics equivalent to that of a set having the same initial parameters and representing continuous NS formation (we refer for details to the “Scenario Machine” of Lipunov et al. 1996b).

A number of runs have been performed using different number of objects (up to a maximum of $\sim 10^3$) and, in addition, tests have been carried out using different seeds for the random orientation of kicks. Statistical fluctuations on the number of stars in each stage are typically of a few percent.

2.2. Accretion physics

The accretion rate was calculated according to the Bondi formula

$$\dot{M} = \frac{2\pi(GM)^2 m_p n(R,Z)}{(V^2+V_s^2)^{3/2}} \simeq 10^{11}\, n\, v_{10}^{-3}\ \mathrm{g\,s^{-1}} \quad (8)$$

where m_p is proton mass, the sound speed V_s is always 10 km s^{-1} and $v_{10} = (V^2+V_s^2)^{1/2}$ in units of 10 $\mathrm{km\,s^{-1}}$. Here and in the following M and R denote the NS mass and radius, which we take equal to $1.4\,M_\odot$ and 10 km, respectively, for all stars. Assuming, for the sake of simplicity, a non–relativistic efficiency $\sim GM/Rc^2$, the accretion luminosity is given by

$$L = \frac{GM\dot{M}}{R}\,. \quad (9)$$

Although the spectrum emitted by accreting NSs may differ rather substantially from a blackbody at the star effective temperature (see Zampieri et al. 1995 for low–field spectra and Zane, Turolla & Treves 1999 for magnetized models) here we assume pure thermal emission. Even in this simplified case, the effective temperature depends on the star dipole field because accretion occurs only at the two polar caps of radius $R_{cap} = R\sqrt{(R/R_A)}$,

$$R_{cap} = 9.5\times10^3\,\mu_{30}^{-2/7} n^{1/7} v_{10}^{-3/7}\ \mathrm{cm}\,; \quad (10)$$

here $R_A \simeq 1.1\times10^{10} n^{-2/7} v_{10}^{6/7} \mu_{30}^{4/7}$ cm is the Alfven radius and μ_{30} is the star magnetic dipole moment in units of 10^{30} G cm^3 (see e.g. Zane et al. 1996a; Konenkov & Popov 1997). The reduced emitting area produces harder spectra, with an effective temperature $\sim$ 3–4 times larger than in the unmagnetized case

$$T_{eff} \simeq 5\times10^8 \mu_{30}^{1/7} n^{13/14} v_{10}^{-39/14}\ \mathrm{K}\,; \quad (11)$$

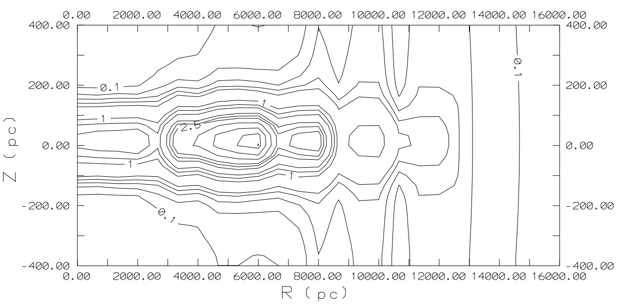

Fig. 1.— The hydrogen number density distribution in the R–Z plane.

typical temperatures are around 100 eV for $V \sim 100$ $\mathrm{km\,s^{-1}}$ for non-evolving magnetic field, and a little bit lower for evolving.

2.3. Period evolution

All neutron stars are assumed to be born with a period $P(0) = 0.02$ s, and a magnetic moment either $\mu_{30} = 1$ or $\mu_{30} = 0.5$. Different distributions of the initial periods, like the one recently proposed by Spruit & Phinney (1998), were also tested and produced very similar results.

The ejector regime begins with the pulsar phase and proceeds also after the breakdown of the coherence condition when the star becomes a dead, or silent, pulsar. In this phase the energy losses are due to magnetic dipole radiation and the period increases in time according to

$$P = P(0) + 3\times10^{-4}\mu_{30}\, t^{1/2}\ \mathrm{s} \quad (12)$$

where t is in yr. 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. For this condition to be met, the period must have reached a critical value

$$P_E(E\to P) \simeq 10\,\mu_{30}^{1/2}\, n^{-1/4}\, v_{10}^{1/2}\ \mathrm{s} \quad (13)$$

which is attained by dipole braking (for a constant field) in a time

$$t_E \simeq 10^9\,\mu_{30}^{-1}\, n^{-1/2}\, v_{10}\ \mathrm{yr}\,. \quad (14)$$

When $P > P_E(E\to P)$ matter can penetrate down to the Alfven radius, but the interaction with the rotating magnetosphere prevents accretion to go any further because of the centrifugal barrier. The NS is now in the propeller phase, rotational energy is lost to the ISM and the period keeps increasing at a rate

$$\frac{dP}{dt} \simeq \frac{\dot{M}\,R_A^2\,P}{I} \simeq K\,P^\alpha\ \mathrm{s\,s^{-1}}\,. \quad (15)$$

Here we take $K = 2.4\times10^{-14}\mu_{30}^{8/7} n^{3/7} v_{10}^{-9/7}$, $\alpha = 1$ (Shakura 1975) and $I = 10^{45}$ g cm^2 is the star moment of inertia.

It should be stressed, however, that our expression for the propeller spin–down is just an approximation. The propeller physics is very complicated and its through understanding requires a full 2–D or even 3–D MHD investigation of accretion onto a rotating dipole (see e.g. Toropin et al. 1999; see also other spin–down formulae for that stage in Lipunov & Popov 1995). The propeller spin–down, as modeled by equation (15), is very efficient and acts on a typical timescale

$$t_P \simeq 1.3 \times 10^6 \, \mu_{30}^{-8/7} \, n^{-3/7} \, v_{10}^{9/7} \ \mathrm{yr} \, . \qquad (16)$$

Numerical simulations (Toropin et al. 1999; Toropin, private communication) seem indeed to confirm that spin–down in the propeller phase is very fast due to the large mass expulsion rate. Note that the present expression for the propeller torque is somewhat different from that adopted by Treves et al. (1993; 1998). 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

$$P_E(P \to E) \simeq 3 \, \mu_{30}^{4/5} v_{10}^{6/7} n^{-2/7} \mathrm{s} \, . \qquad (17)$$

Note that the transitions $P \to E$ and $E \to P$ are not symmetric because the two periods (13) and (17) derive from the same physical condition but evaluated at different radii, as first discussed by Shvartsman in the early '70s.

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

$$P_A(P \to A) \simeq 420 \, \mu_{30}^{6/7} \, n^{-3/7} \, v_{10}^{9/7} \ \mathrm{s} \, . \qquad (18)$$

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

$$P_{eq} = 2.6 \times 10^3 \, v_{(t)10}^{-2/3} \, \mu_{30}^{2/3} \, n^{-2/3} \, v_{10}^{13/3} \ \mathrm{s} \qquad (19)$$

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

Actually the condition that $P \geq P_A$ is not sufficient to guarantee that matter is captured at the accretion radius. At the very low accretion rates expected for fast, isolated NSs, it could be that the Alfven radius is larger than the accretion radius. The condition $R_A < R_{ac}$ translates into a limit for the star velocity

$$v < 410 \, n^{1/10} \mu_{30}^{-1/5} \ \mathrm{km\,s^{-1}} \, . \qquad (20)$$

Above this velocity the NS behaves as a georotator and it experiences a torque which is computed in the same way as in the propeller stage. The star can enter the georotator phase only from the propeller or accretor stage.

Figure 2 illustrates the various possible stages for a NS 10^{10} yr old as a function of the star velocity and magnetic field for a constant ambient density of 1 $\mathrm{cm^{-3}}$. The propeller region in figure 2 is very small, as a consequence of the extremely efficient spin–down implied by equation (15) with our choice of the parameters α and K.

3. Results and discussion

In this section, we present the results of our numerical simulations both in the cases of a constant and of a decaying magnetic field.

3.1. The NS census for a non–decaying field

Here we consider two values for the magnetic dipole moment ($\mu_{30} = 0.5$ and $\mu_{30} = 1$) as representative of 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 3. Statistical errors are typically $\sim 2\%$. Propellers and Georotators are much less abundant and never exceeds $\sim 1\%$ of the total number. In addition, their fractions oscillate intrinsically because of the changes in the velocity and in the ISM density along the star trajectory. These effects add further noise to the statistical fluctuations and, given the small number of sources in these two states, prevent any definite conclusion about the dependence of the fractions from the mean kick velocity. We note that the fraction of Accretors increases with the field strength, in agreement with the findings of Livio Xu & Frank (1998) and Colpi et al. (1998). Highly magnetized NSs suffer, in fact, a more severe spin–down during the Ejector and Propeller phases and reach the accretion phase earlier in their history. For large enough mean kick velocities (> 400 km $\mathrm{s^{-1}}$ for $\mu_{30} = 1$ and > 300 km $\mathrm{s^{-1}}$ for $\mu_{30} = 0.5$) the fraction of accretors becomes very small and again results become statistically uncertain. We note also that the numerical simulation produces a picture of the present status of the Galactic NS population which is consistent with that emerging from figure 2. In fact, if we assume that the velocity gives a measure of the average kick, we see, with reference to $\mu_{30} = 1$, that Accretors are more abundant than

Ejectors up to $\sim 100\,\mathrm{km\,s^{-1}}$, Propellers are extremely rare and Georotators nearly absent. This is precisely what figure 3 shows.

To obtain an estimate of the number of accreting sources in the Solar vicinity (taken to be a sphere of radius 140 pc centered on the Sun), we used all the stars contained in a torus of the same radius located at 8 kpc from the center of the Galaxy. The result was then rescaled to the volume of interest and is shown in figure 4. Here, and in the following the total number of Galactic NSs was assumed to be 10^9. As expected, the local density is a sensitive function of the kick velocity and varies between $n \sim 8.5 \times 10^{-3}$ pc^{-3} and $n \sim 6 \times 10^{-4}$ pc^{-3} for $\langle V \rangle = 0$ and 190 km s^{-1} respectively. These figures should be compared with $n \sim 1.4 \times 10^{-3}\,(N/10^9)$ pc^{-3} as derived by Paczyński (1990) for a zero mean velocity and with $n \sim 3 - 7 \times 10^{-4}\,(N/10^9)$ found by Blaes & Madau (1993) and Zane et al. (1995) for an initial mean velocity of ~ 60 km s^{-1}. The values of the local density of isolated NSs are thus consistent with these previous estimates.

The density of isolated NSs projected onto the Galactic plane is $\sim 2.4 \times 10^5\,(N/10^9)$ kpc^{-2} for average initial velocities ~ 200 km s^{-1} and a scaleheight of 200 pc. This figure is close to the one deduced by Neühauser & Trümper (1999) from radio pulsars observations (Lyne et al. 1998) with the assumption of a pulsar lifetime $\sim 10^7$ yr. We would like to note, however, that a projected density $\sim 10^5$ kpc^{-2} is now obtained for $N = 10^9$ instead of 10^8 (as in Madau & Blaes 1994; see also Neühauser & Trümper 1999) because of the larger mean velocity at birth. 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 pulsars observations. For the time being, it is still 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 (see Colpi et al. 1996). Radio pulsars are observed only in a fraction of SNRs (see e.g. Kaspi 1996; Frail 1998), and even some of these coincidences are doubtful, so there is a serious possibility that the total number of NSs derived from radio pulsar statistics is only a lower limit.

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} at energies ~ 100 eV (the con-

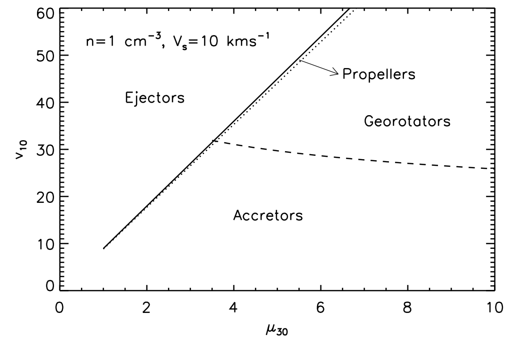

Fig. 2.— The different stages of old NSs at present as a function of the star velocity and magnetic dipole moment.

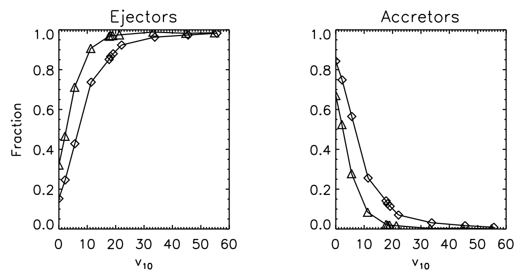

Fig. 3.— Fractions of NSs in the different stages vs. the mean kick velocity for $\mu_{30} = 0.5$ (triangles) and $\mu_{30} = 1$ (diamonds); typical statistical uncertainty is $\sim 2\%$.

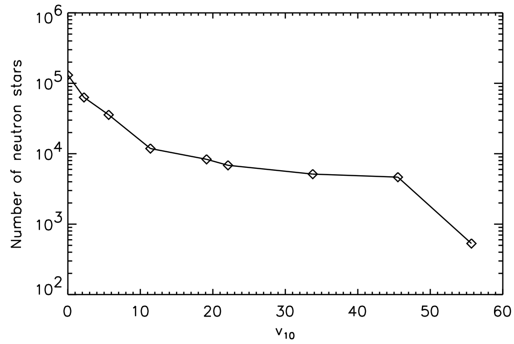

Fig. 4.— Total number of NSs in the Solar vicinity ($R < 140$ pc) for $\mu_{30} = 1$.

tribution from sources at larger distances is found to be negligible). This flux limit should correspond to a RASS count rate of 0.01 cts s^{-1} for a blackbody spectrum, once the interstellar absorption and the ROSAT response function are accounted for. The results are illustrated in figure 5 (at 300 km s^{-1} and above statistical errors are dominant). As expected, the dependence of the number of visible sources on the kick velocity is rather strong. 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 analyses on the number of isolated NSs in the RASS (Neühauser & Trümper 1999) indicate that the upper limit is below 10. This implies a *lower limit* for the mean kick velocity at birth of ~ 200 km s^{-1} for a total number of stars $\sim 10^9$.

This result is in agreement with the estimates derived from pulsar statistics. An important aspect is that our results exclude the possible presence of a consistent low–velocity population at birth, which exceeds that contained in the gaussian with $\langle V \rangle > 200$ km s^{-1} ($\sim 1\%$ for $\langle V \rangle < 70$ km s^{-1}).

3.2. The NS census for a decaying field

The time evolution of the magnetic field in isolated NSs is still a very controversial issue and no firm conclusion has been established as yet. A strong point is that radio pulsar observations (see e.g. Lyne et al. 1998) seem to rule out fast decay with typical times less than ≈ 10 Myr, but this does not exclude the possibility that B decays over much longer timescales ($t_d \sim 10^9 - 10^{10}$ yr). For this reason we have investigated to what extent the decay of the B–field influences the results presented in the previous section. We refer here only to a very simplified picture in which $B(t) = B(0)\exp(-t/t_d)$ and no attempt is made to justify this law on a physical ground. In this respect we just mention that detailed models predict both exponential (quite similar to the one assumed here) and non–exponential decay (e.g. a power–law, Urpin & Konenkov 1997). Calculations have been performed for $t_d = 1.1 \times 10^9$ yr, $t_d = 2.2 \times 10^9$ yr and $\mu_{30}(0) = 1$. Since no bottom field was specified, the magnetic moment becomes very low for stars born $\sim 10^{10}$ yr ago ($\sim 10^{26}$ G cm^3 and $\sim 10^{28}$ G cm^3 for the two values of t_d respectively).

Results are summarized in figure 6. As it is expected (see Colpi et al. 1998), the number of Propellers is significantly increased with respect to the non–decaying case, while Ejectors are now less abundant. Georotators are still very rare, $\lesssim 1\%$, and are not shown in figure 6. The fraction of Accretors is approximately the same for the two values of t_d, and, at least for low mean velocities, is comparable to that of the non–decaying field while, at larger speeds, it seems to be somehow higher. This shows that the fraction of Accretors depends to some extent on how the magnetic field decays. We know that a core field decaying initially but then freezing produces an underabundance of Accretors relative to a constant field (Livio Xu & Frank (1998) and Colpi et al. (1998)) because NSs persist in the Ejector phase never approaching the Propeller or the Accretor phase. By contrast, a fast and progressive decay of B ($t_d < 10^9$ yr) would lead to an overabundance of Accretors because this situation is similar to "turning off" the magnetic field, i.e., quencing any magnetospheric effect on the accreting matter (see Popov & Prokhorov 1999 (in press)).

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 ~ 10 non–optically identified sources can be accreting ONSs. This implies that the average velocity of the NS 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 ONSs are slow objects, our results exclude also the possibility that the present velocity distribution of NSs is richer in low–velocity objects

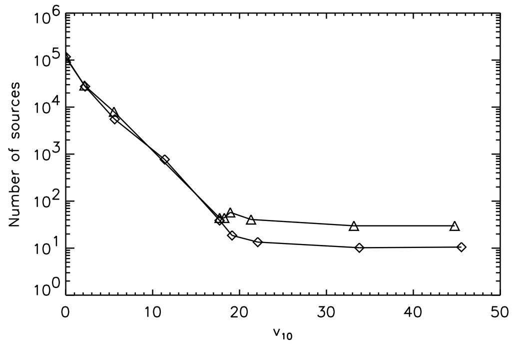

Fig. 5.— Number of accreting NSs in the Solar vicinity above the ROSAT All Sky Survey detection limit for a constant ($\mu_{30}=1$, diamonds) and decaying field ($t_d = 2.2 \cdot 10^9$ yrs, triangles).

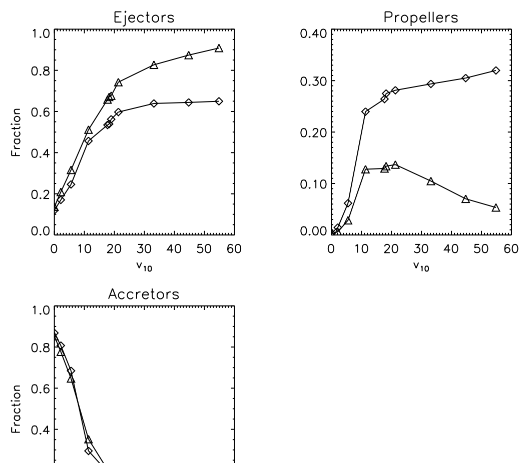

Fig. 6.— Fractions of NSs in the different stages vs. the average kick velocity for a decaying field with an e–folding time $t_d = 2.2 \times 10^9$ yrs (triangles) and $t_d = 1.1 \times 10^9$ yrs (diamonds).

with respect to a Maxwellian. The paucity of accreting ONSs seem therefore to lend further support in favor of neutron stars as very fast objects.

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