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LOG N – LOG S DISTRIBUTIONS OF ACCRETING AND COOLING ISOLATED NEUTRON STARS

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ABSTRACT

We model populations of isolated neutron stars in the Galaxy following their orbital and magneto-rotational evolution. It is shown that accretors become more abundant than coolers at fluxes below $\sim 10^{-13}$ erg cm^{-2} s^{-1}, and one can predict that about one accreting neutron star per square degree should be observed at the *Chandra* and *Newton* flux limits of $\sim 10^{-16}$ erg cm^{-2} s^{-1}. The soft ROSAT sources associated with isolated neutron stars can be relatively young cooling objects only if the neutron star birth rate in the Solar vicinity during the last $\sim 10^6$ yr is higher than that inferred from radiopulsar observations.

Subject headings: accretion, accretion disks — stars: kinematics — stars: magnetic fields — stars: neutron — stars: statistics — X–rays: stars

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. 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 and Motch 2000 for recent reviews). The ROSAT candidates, although relatively bright (up to ≈ 1 ct 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 (Zane, Turolla & Treves 2000; Treves et al. 2000). Up to now only two optical counterparts have been identified (RXJ 1856, Walter & Matthews 1997, for which a distance estimate of ~ 60 pc has been very recently obtained, Walter 2000, and RXJ 0720, Kulkarni & Van Kerkwick 1998). 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.

In this *Letter* 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 & Colpi 1991; Madau and Blaes 1994; Manning et al. 1996) assuming a NSs velocity distribution rich in slow stars ($v \lesssim 100$ km s^{-1}). More recent measurements of pulsar velocities (e.g. Lyne & Lorimer 1994; Hansen & Phinney 1997) and upper limits on the observed number of accretors in ROSAT surveys (Danner 1998a, b) point, however, to a larger NS mean velocity (see Treves et al. 2000 for a critical discussion). Recently Neühauser & Trümper (1999, NT99 hereafter) compared the number count distribution of the ROSAT isolated NS candidates with those of accretors and coolers. Here we address these issues in greater detail, also in the light of the latest contributions to the modeling of the evolution of Galactic NSs (Popov et al. 2000, P2000 hereafter). In §2 we use a population synthesis model, developed in P2000, to trace the properties of the NS spin, magnetic field and accretion luminosity in the Galactic potential using a detailed map of the interstellar medium (ISM). Cooling NSs are explored separately

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in §3 within a simpler model of local sources. Results are discussed in §4.

2. ACCRETING ISOLATED NEUTRON STARS

The census model adopted here follows closely that developed in P2000. All NSs are born in the Galactic plane, their birth rate is taken to be proportional to the square of the ISM density and is constant in time. Initially a NS has a circular velocity fixed by its position in the Galactic plane and determined by the Galactic potential. To this, an additional kick velocity with random orientation and modulus selected from a Maxwellian distribution is imparted.

Time resolution is adapted to follow in detail the different evolutionary phases the star experiences. NSs are born in the ejector (E) phase and then, as braking due to electromagnetic torques increases the period, come to the propeller (P) phase. Further spin-down, produced by accretion torques, may drive the star in the accretion (A) phase when matter can penetrate the magnetosphere reaching the stellar surface (see e.g. Lipunov 1992). Accretion is then assumed to proceed at the local Bondi rate and the large scale ISM distribution is mapped as in P2000. The small scale structure of the ISM ($\approx$ 100AU-1 pc, see e.g. Meyer & Lauroesh 1999; Treves et al. 2000), has not been taken into account as it would produce an unacceptable increase of the computing time, leading to a worse statistics. A detailed mapping of the ISM on all scales is fundamental in assessing the observability of single, luminous sources (see Zane et al. 1996), but the effects produced by its multiphase structure on the evolution of the entire NS population are likely to average out.

Here we consider only the simplest picture, where the star magnetic field is constant and the dipole moment μ has a log-gaussian distribution, similar to that observed in radiopusars ($\langle \log \mu \rangle = 30.06$, $\sigma = 0.32$ in CGS units).

The magneto-rotational evolution is followed using essentially the same approach as in P2000. In particular, the typical values of the transition periods are ~ 25 s and ~ 1500 s for E$\to$ P and P$\to$ A transitions, respectively. As soon as the star enters the accretor stage, the period is set to the value typical of an accretor embedded in a turbulent medium (Lipunov & Popov 1995; Konenkov & Popov 1997).

The statistics of accretors was improved by a factor > 10 relative to P2000 by evolving only stars from the low-velocity tail ($v < 100$ km s^{-1}) of a Maxwellian with $\langle v \rangle = 300$ km s^{-1}. This assumption appears justified since the time spent in the ejector phase increases with velocity, $t_E \sim 10^{10}\, \mu_{30}^{-1} n^{-1/2} v_{100}$ yr . The present choice for $\langle v \rangle$ follows from radiopulsar observations and current limits on the detection of accreting NSs (P2000). Results can be easily scaled to any $\langle v \rangle > 200$ km s^{-1}.

Nearly all highly magnetized isolated NSs in the velocity range considered here become accretors, and in calculating the $\log N - \log S$ distribution we obtain good statistics for fluxes $< 10^{-11}$ erg cm^{-2} s^{-1}. At larger fluxes the number of sources is too small to give reliable counts, but the extrapolation $\log N \sim -(3/2) \log S$ can be safely used for $\log S \gtrsim -11$.

Our main results are presented in Figures 1 and 3, and refer to a total of 10^9 NSs in the Galaxy. The $\log N - \log S$ distribution of accretors is computed for sources within a distance of 5 kpc, together with the distributions of velocity, accretion rate and effective temperature (calculated adopting as effective surface the polar cap area). Isolated NSs with fields $< 0.5 \times 10^{11}$ G never appear as accretors in any run. The brightest accretors have luminosities $\sim 10^{32}$ erg s^{-1}, but for the majority of them $L \approx 10^{29} - 10^{30}$ erg s^{-1}. Our sources are relatively hot, with a mean effective temperature 300-400 eV and for them absorption can be neglected. We predict, on average, about 1 source per square degree, in the energy range 0.5-2 keV, for limiting fluxes about 10^{-16}–10^{-15} erg cm^{-2} s^{-1}. This implies $\sim 3 \times 10^4$ sources in the whole sky. Note that they are significantly concentrated toward the Galactic plane with a center-anticenter asymmetry.

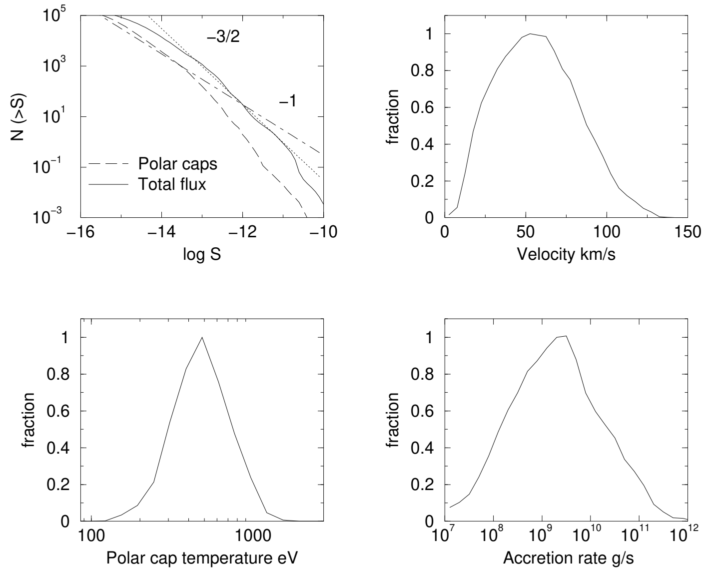

FIG. 1.— Upper left panel: the $\log N - \log S$ distribution for accretors within 5 kpc from the Sun. The two curves refer to emission from the entire star surface and to polar cap emission in the range 0.5-2 keV; two straight lines with slopes -1 and -3/2 are also shown for comparison. From top right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

3. COOLING NEUTRON STARS

Soon after their birth in a type II supernova event, cooling NSs emit X-ray luminosities as high as $\sim 10^{34}$ erg s^{-1} for a few thousands years. Before disappearing from the X-ray sky, they shine as faint soft sources ($L \sim 10^{32}$ erg s^{-1}) for about a million year (e.g. Yakovlev et al. 1999).

In the determination of the log$N$-log$S$, the cooler sample should in principle be drawn from the same parent population as accretors. However, as their total number is quite low ($\approx 10^{-4}$ of the total number of NS in the Galaxy) owing to the short duration of the cooling phase, the results would be affected by the very poor statistics. Notice however that coolers can travel only a distance ≈ 400 pc during their lifetime and have softer spectra than accretors, so they appear mostly as a local population of sources (due to interstellar absorption).

For this reason, we prefer to approximate their spatial distribution around the sun as homogeneous with a scale height of ~ 450 pc. We take cooling NSs as "standard candles" with $L = 10^{32}$ erg s^{-1}, giving off a black-body spectrum with effective temperature ~ 50 eV. The duration of the cooling phase is taken to be 10^6 yr, according to the "slow cooling" scenario (see NT99). We used two typical values for the total NS spatial density: $0.33 \times 10^{-3}\,\mathrm{pc}^{-3}$ and $3.3 \times 10^{-3}\,\mathrm{pc}^{-3}$. The former estimate follows from radiopulsar statistics and was used by NT99, while the latter corresponds to a total population of 10^9 NSs, as implied by constraints on nucleosynthetic yields and historic supernova rates (Arnett et al. 1989; van den Bergh & Tammann 1991). Accordingly, coolers have a mean density of $0.33 - 3.3 \times 10^{-7}\mathrm{pc}^{-3}$.

The ISM structure is treated in a very simple way. The ISM density inside the Local Bubble of radius $r_l = 140$ pc (Sfeir et al. 1999) is $n = 0.07$ cm^{-3}. At larger distances the interstellar gas is assumed to be uniformly distributed in a disk of half-thickness 450 pc with $n = 1$ cm^{-3}.

Results are shown in Figure 2, where we compare the observed distribution of ROSAT candidates with that of coolers, as predicted by the present model (including absorption) and by NT99, the latter obtained for a total NS number $N_{tot} = 2 \times 10^8$. As it is apparent, coolers dominate over accretors at large fluxes (for the same N_{tot}), essentially because of their much higher luminosity (10^{32} vs. $10^{29} - 10^{30}$ erg s^{-1}).

This simple model reproduces the most important feature, the "flattening" of the $\log N - \log S$ distribution outside the Local Bubble. Such strong flattening can help to explain the observed data, if one assumes that most of the brightest isolated NSs are identified (Schwope et al. 1999).

The value of the flux at which the distribution flattens out (the "knee") depends on the size of the Local Bubble r_l. The ISM densities and the duration of the cooling time affect instead the number of sources. Since the cooling time can be an important parameter, the comparison of theoretical and observed distributions could, in principle, help in discriminating between "fast" and "slow" cooling models.

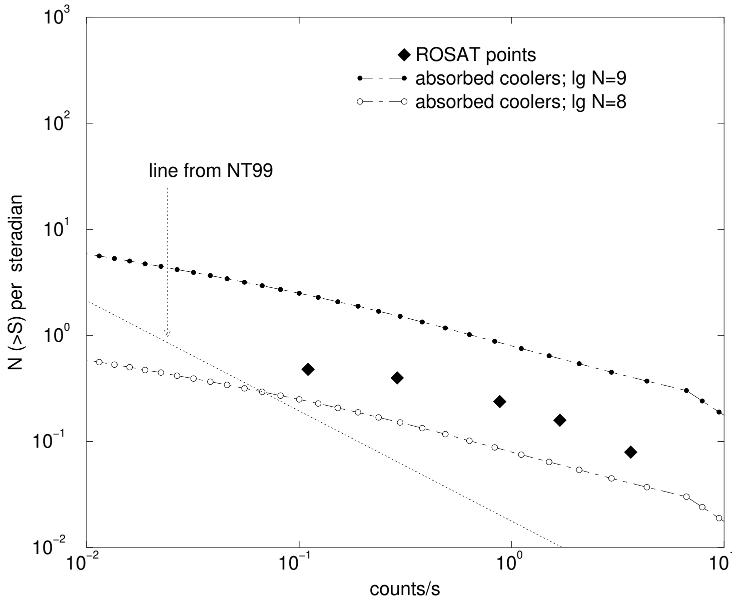

FIG. 2.— The $\log N$–$\log S$ for coolers. The upper curve (filled circles) correspond to a NS density of 3.3×10^{-3} pc^{-3} and the lower one (open circles) to 3.3×10^{-4} pc^{-3}; here $r_l = 140$ pc.

4. DISCUSSION

The statistical analysis presented in the previous sections shows that both scenarios, accretors and coolers, have difficulties in explaining, under usual assumptions, the observed properties of isolated NS ROSAT candidates. The main problem is to produce enough sources that are, at the same time: i) relatively bright (high count rates, $\gtrsim 0.1$ cts s^{-1}); ii) close (low absorption $N_H \lesssim 10^{20}\mathrm{cm}^{-2}$); iii) soft ($T_{eff} \sim 50 - 100$ eV); iv) slowly rotating (for two candidates, RX J0720 and RX J0420, the detected periods are 8.4 and 22.7 s).

Polar cap accretion for a non-decaying magnetic field, $B \approx 10^{12}$ G, cannot produce enough bright sources and the emitted spectrum is likely to be harder, see Figure 1. Moreover, accretors are expected to have much larger periods, $P \gtrsim 10^3$ s. On the other hand, relatively young cooling NSs can be spun down to periods ~ 20 s in $< 10^6$ yrs (when they are still hot) only for $B \gtrsim 10^{14}$ G, since $P \sim 15\, B_{14} (t/10^6\,\mathrm{yr})^{1/2}$ s for dipole losses. If all NSs experience an initial radiopulsar phase, their total number in the Galaxy would be about $(1-3) \times 10^8$ (Lyne et al. 1998). In this case there will be not bright enough isolated NSs in the Solar vicinity in both scenarios.

If $N_{tot} \sim 10^9$, coolers can explain the large number of bright close-by sources and their typical temperatures (see Figure 2). However, the problem of reproducing the observed periods still remains, unless the progenitors of the ROSAT pulsating candidates are NSs born with long periods, which never passed through the pulsar phase; alternatively they could be magnetars with ultra-high fields, as suggested by Heyl & Kulkarni (1998). If proved correct, the "fast" cooling scenario, in which the duration of the active X-ray phase is shorter, would make again problematic to account for the observed bright sources.

In the accretion scenario, increasing the total number of NSs is also a need. As already shown by Livio et al. (1998) and Colpi et al. (1998), magnetic field decay can explain the low temperatures and periods. Decay can both increase and decrease number of accreting isolated NSs (Popov, & Prokhorov 2000). But a complete statistical analysis is still to come.

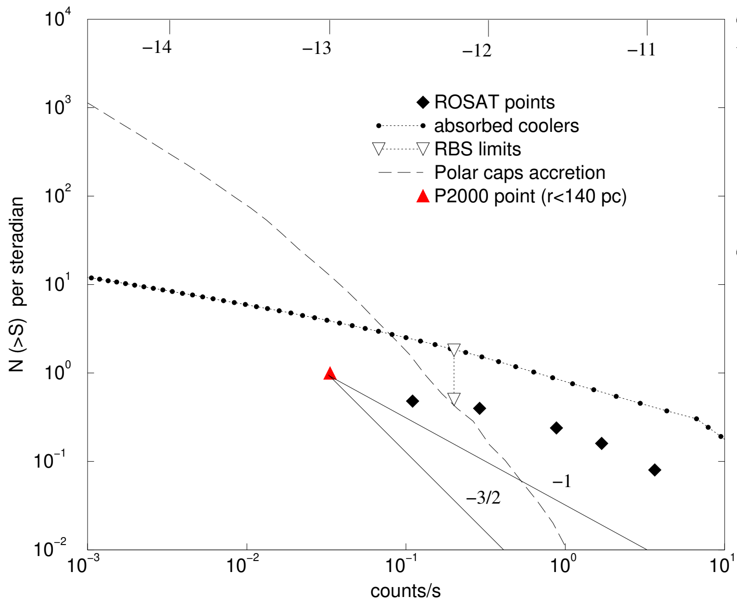

FIG. 3.— Comparison of the log N − log S distributions for accretors and coolers together with observational points, the naive log$N$ − log$S$ from P2000 and the ROSAT Bright Survey (RBS) limit (Schwope et al. 1999). The scale on the top horizontal axes gives the flux in erg cm^{-2}s^{-1}.

In any case, 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.

Note that the number of accretors (of all luminosities) in the Galaxy is found to be about two orders of magnitude larger than the number of young coolers: few percents versus 0.01% of the total number of isolated NSs. But on average accretors are 3 orders of magnitude fainter than a typical cooler. 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}. This is illustrated in Figure 3 in which we summarize the main outcome of our simulations.

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