ISOLATED NEUTRON STARS DISCOVERED BY ROSAT

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ABSTRACT

ROSAT has discovered a new group of isolated neutron stars characterized by soft black-body like spectra (kT $\sim$ 50-120 eV), apparent absence of radio emission and no association with supernovae remnants. So far only six such sources are known. A small fraction of these stars exhibit X-ray pulsations with relatively long periods of the order of 10 sec. Two very different mechanisms may be envisaged to explain their properties. The neutron stars may be old and re-heated by accretion from the ISM in which case their population properties could provide information on past stellar formation and secular magnetic field decay. Alternatively, this group may at least partly be made of relatively young cooling neutron stars possibly descendant from magnetars. We review the last observational results and show how they can shed light on the evolutionary path of these new objects within the whole class of isolated neutron stars.

KEYWORDS: neutron stars; pulsars; magnetars

1. INTRODUCTION

The vast majority of the 10^8-10^9 isolated neutron stars (INS) present in the Galaxy should be virtually undetectable using current observational means. Young cooling neutron stars might emit thermal X-rays during the first $\sim 10^6$ yr and their pulsed radio emission will reveal them up to ages of $\sim 10^8$ yr. Recycled millisecond pulsars are old objects but their previous accreting binary phase may have altered their physical properties in particular the magnetic field strength. In this context, the possibility that a sizeable fraction of the entire 'fossil' population is re-heated by accretion from interstellar medium and becomes detectable in the EUV / X-ray domain is exciting. This could allow an observational study of old neutron stars and give access to information on past stellar formation, heating and cooling mechanisms and magnetic field decay. This idea was first proposed by Ostriker, Rees & Silk (1970). Population synthesis models were later computed by Treves & Colpi (1991), Blaes & Madau (1993) and Madau & Blaes (1994). A recent and extensive review on current issues can be found in Treves et al. (1999). Early models predicted that a rather large number of ROSAT XRT all-sky survey (RASS) sources could be accreting INS, initiating several optical identification campaigns. In this paper we shall describe the general observational properties of the INS discovered by ROSAT, discuss the possible X-ray powering mechanisms, consider what iden-

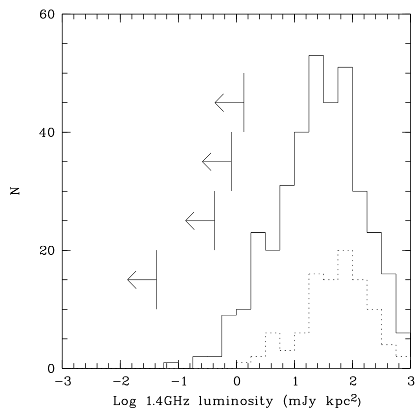

FIGURE 1. Upper limits on 1.4GHz radio luminosity of ROSAT discovered INS. Vertical displacement is there only for readability. Histograms represent the distribution of observed luminosities of radio pulsars as in Taylor et al. (1993) (Total population is the continuous line, pulsars with ages below 10^6 yr is the dashed line)

tification campaigns can tell us so far on the total population and discuss in more details the pulsating sources.

2. GENERAL PROPERTIES

The group of INS discovered by ROSAT shares a rather well defined set of properties. Although each of these features may be present individually in sub groups of INS (e.g. some radio pulsars have very soft X-ray spectra and some X-ray emitting radio quiet INS are found in SNR environments), the properties characterizing this new group are never encountered together in previously known classes of INS.

Soft X-ray spectra. All ROSAT discovered INS exhibit soft X-ray spectra which at the energy resolution of the PSPC can be very well fitted by blackbody models with temperatures in the range of $\sim$ 50 to 120 eV. No bright X-ray hard component seems to be present, at least at the level encountered in most X-ray detected radio pulsars. Another common spectral feature is the low N_H towards these sources ($\sim 10^{20}$ cm^{-2}) which implies distances of the order of 100 to 1000 pc at most.

No strong radio emission. The absence of detected bright radio emission seems to be also a common feature although not all members have been surveyed yet. At present, constraints on radio emission are mostly based on the FIRST and NVSS surveys. We list in Table 1 various upper limits on luminosity gathered for a subset of INS candidates. In Fig. 1 we show the position of these upper limits with respect to observed 1.4 GHz luminosity distribution of radio pulsars.

ROSAT discovered INS are undoubtedly less radio luminous than most known radio pulsars. The difference is stricking if one assumes that these are young cooling

TABLE 1. Upper limits on radio emission from ROSAT discovered INS

ROSAT source	Frequency GHz	Assumed distance (kpc)	Max L mJy kpc^2	Survey
RX J1856−3754	0.43	0.13	0.058	Parkes survey
	1.4		0.042	NVSS
RX J0720−3125	1.4	0.41	0.420	NVSS
RX J1605+3249	1.4	0.70	0.400	FIRST
RX J1308+2127	1.4	1.20	1.350	FIRST

objects with ages of less than about 10^6 yrs. However, targeted radio observations should easily improve on current upper limits.

No association with SNR. ROSAT and Einstein observatories have discovered a number of X-ray bright but apparently radio quiet neutron stars associated with SNRs (Gotthelf et al. 1997, Brazier & Johnston 1999). Their X-ray spectra, although often thermal like are in general significantly hotter than those of the group of INS discussed here. In contrast, the fact that none of the INS considered here lies close to an SNR suggests ages older than $\sim 10^5$ yr.

No long term variability. ROSAT was able to monitor the mean X-ray luminosity of some candidates over several years, basically from the all-sky survey time till the last operational phases. EXOSAT and Einstein have also serendipitously observed some of these targets further extending the time base. In the cases investigated in details no evidence for X-ray variability over months or years time scale exist with very stringent upper limits of the order of few percents (Walter et al. 1996, Haberl et al. 1997, Motch et al. 1999).

Long rotation periods. At least one of the INS candidates, RX J0720-3125 exhibits X-ray pulsations with a period of 8.39 s (Haberl et al. 1997). Another case is RX J0420−5022 which is possibly pulsating at 22.7 s (Haberl et al. 1999). The spin period of other candidates is not known but this issue may be settled by forthcoming XMM observations. These long spin periods are most unusual for radio pulsars. We shall see below that the long periods have profound impact on the possible evolutionary status of these objects.

2.1. Optical identifications

Only the two X-ray brightest candidates have a secure optical identification. The ROSAT source RX J1856.5−3758 was identified by Walter et al. (1996) with a V = 25.6, U-V = −1.2 object. A faint B = 26.1-26.5 blue star is also the likely counterpart of RX J0720-3125 (Motch & Haberl 1998, Kulkarni & van Kerkwijk 1998). In these two cases, the optical continuum lies only 1.4 and 1.7 magnitude respectively above the Rayleigh-Jeans tail of the blackbody seen in soft X-rays. For the remaining candidates, the identification with an INS eventually rests on the absence of optical

TABLE 2. The catalogue of isolated neutron stars discovered by their X-ray emission

ROSAT source	PSPC cts/s	kT eV	N_H $10^{20}\,cm^{-1}$	P s	B mag	References
RX J1856−3754	3.64	57 ± 1	1.4 ± 0.1	-	25.8	1
RX J0720−3125	1.64	79 ± 4	1.3 ± 0.3	8.39	26.5	2
RX J1605+3249	0.90	92 ± 6	1.1 ± 0.4	-	>25	3
RX J0806−4123	0.38	78 ± 7	2.5 ± 0.9	-	>24	4
RX J1308+2127	0.29	113 ± 14	2.0 ± 0.4	-	>26	5
RX J0420−5022	0.14	<85	2.0	22.7:	>25.2	6
MS 0317.7−6647	∼ 0.03	180 ± 30	40 ± 20	-	> 21.4	7

References: 1) Walter et al. (1996), 2) Haberl et al. (1997), 3) Motch et al. (1999), 4) Haberl et al. (1998), 5) Schwope et al. (1999), 6) Haberl et al. (1999), 7) Stocke et al. (1995).

signatures of other possible soft X-ray emitters such as magnetic CVs or soft AGNs.

2.2. The catalogue

We list in Table 2 the main properties of the INS discovered so far on the basis of their X-ray emission. In almost all cases, their nature was established by ROSAT observations although some of them already had Einstein or EXOSAT detections. MS 0317.7-6647 (Stocke et al. 1995) is a particular case as its X-ray energy distribution undergoes very high absorption. Also, its INS nature is not entirely clear since an identification with a very massive accreting black hole in the field spiral galaxy NGC 1313 is not excluded.

3. X-RAY POWERING MECHANISMS

A number of possible mechanisms leading to production of X-rays from INS may be envisaged. Basically, the X-ray luminosity may be extracted from spin down as 'normal' radio pulsars do, from cooling, or the neutron star may be re-heated by accretion of interstellar material. We consider below in some details each of these mechanisms.

3.1. Rotation

Becker & Trümper (1997) showed that for 'normal' radio pulsars, the X-ray luminosity is tightly linked to rotational energy loss with $L_X \sim 10^{-3}\ \dot{E}$. Wang et al. (1999) pointed out that at least in the case of RX J0720−3125 this mechanism could not work since the observed X-ray luminosity was more than twice the upper limit on spin down power ($\dot{P} \leq 0.8\ 10^{-12}$, Haberl et al. 1997). However in the absence of spin period measurements and derivatives this mechanism cannot be ruled

TABLE 3. Brightest X-ray pulsars in the ROSAT PSPC instrumental system after Becker & Trümper (1997)

Pulsar name	PSPC cts/s	P ms	$\mathrm{Log}(P/2\dot{P})$ years	Note
Crab	17.8	33.4	3.10	
Vela	3.40	89.29	4.05	
B0656+14	1.92	384.87	5.05	cooling pulsar
B1055-52	0.35	197.10	5.73	cooling pulsar
J0437-47	0.20	5.75	9.50	

out for other INS candidates. All radio pulsars bright enough to have a constraining ROSAT PSPC spectrum exhibit a rather hard power law component which is thought to be the signature of intense magnetospheric activity (Becker & Trümper 1997). The absence of a luminous hard X-ray tail above the thermal component in ROSAT discovered INS is a general argument against a rotationally driven origin of X-rays.

3.2. Cooling

Blackbody temperatures in excess of 50 eV imply ages younger than $\sim 10^6$ yr for standard cooling curves while the absence of nearby SNR sets a lower limit of $\sim 10^5$ yr. Among the X-ray emitting radio pulsars listed by Becker & Trümper (1997) two middle aged (10^5-10^6 yr) pulsars (PSR 0656+14 and PSR 1055-52) exhibit in addition to the power law a clear thermal component believed to be due to cooling from the neutron star surface. A luminous thermal component is probably also present in the younger (10^4-10^5 yr) Vela type pulsars. In PSR 0656+14 the soft blackbody dominates the 0.1-2.4 keV energy distribution and has characteristics ($T_{bb} = 87$ eV, $N_H = 1.9 \pm 0.4\ 10^{20}$ cm^{-2}) quite similar to those of the INS discussed here. In the case of RX J1605+3249 for instance, Motch et al. (1999) show that owing to the lower statistics, a hard component of similar intensity as in PSR 0656+14 would not have been detected nor would the 0.384 s period with a 9% pulsed fraction have been seen. In this context, a natural and simple explanation for the absence of radio emission from an otherwise X-ray bright and nearby source is that the radio beam does not sweep the earth. The proportion of the sky swept by the radio beam decreases with increasing periods and is of the order of 0.3 for the period range of cooling pulsars (Biggs 1990). In the range of PSPC count rates covered so far there are two cooling radio pulsars (see Table 3). Although this is small number statistics, the picture is in fact consistent with the entire ROSAT discovered population being cooling radio pulsars whose beam remains undetected because it does not cross the earth.

3.3. Accretion from interstellar medium

Accretion of interstellar matter onto old neutron stars can produce X-ray luminosities large enough to detect a sizeable fraction of the total galactic population. Assuming Bondi-Hoyle accretion, the mass accretion rate is $\dot{\mathrm{M}} \sim 10^{10}$ n $(\mathrm{V}/40\,\mathrm{kms}^{-1})^{-3}$ $\mathrm{g\,s}^{-1}$ with V the neutron star velocity with respect to interstellar medium and n the mean density. The temperature of the polar cap heated by accretion is $\mathrm{T_{bb}} \sim 20$ $(\dot{\mathrm{M}}/10^{10}\mathrm{g\,s}^{-1})^{1/4}$ $\mathrm{f}^{-1/4}$ eV with f the relative surface area of the polar cap. However, before matter can reach the neutron star surface a number of conditions must be fulfilled. The first one is that ram pressure at accretion radius exceeds pulsar momentum flux otherwise the star is in the ejector state. This requires the spin period to be less than ~ 9 $(\mathrm{B}/10^{12}\mathrm{G})^{1/2}$ $\mathrm{n}^{-1/4}$ $(\mathrm{V}/40\,\mathrm{kms}^{-1})^{1/2}$ s. Magnetic dipole braking allows to reach this period in ~ 5 $(\mathrm{B}/10^{12}\mathrm{G})^{-1}$ $\mathrm{n}^{-1/2}$ $(\mathrm{V}/40\,\mathrm{kms}^{-1})$ Gyr (Blaes & Madau 1993). The most constraining condition is that the corotation radius must be larger than the Alfven radius. For the low accretion rates prevailing here, this condition requires very slow rotation $\mathrm{P_{rot}} \geq 3000$ $(\mathrm{B}/10^{12})^{6/7}$ $\mathrm{n}^{-3/7}$ $(\mathrm{V}/40\,\mathrm{kms}^{-1})^{9/7}$ s. Dipole magnetic radiation is not efficient enough to slow down the neutron star on a reasonable time scale. Braking is probably achieved by the propeller mechanism which acts on a short time scale of ~ 0.8 $(\mathrm{B}/10^{12}\mathrm{G})^{-11/14}$ $\mathrm{n}^{-17/28}$ $(\mathrm{V}/40\,\mathrm{kms}^{-1})^{29/14}$ Gyr (Blaes & Madau 1993).

4. CONSTRAINTS ON POPULATIONS OF X-RAY EMITTING ISOLATED NEUTRON STARS

The first constraints came from the general identification campaigns which aimed at a complete census of the RASS source population at different flux levels and galactic latitudes. In addition a number of projects specifically searching for INS were initiated. Zickgraf et al. (1997), Motch et al. (1997), Belloni et al. (1997) and Danner et al. (1998) reported on deep surveys in small areas including molecular clouds. Shallow surveys of large areas were performed by Manning et al. (1996), Bade et al. (1998) and Thomas et al. (1998), among others. These campaigns led to the discovery of the handful of candidates discussed here. They also yielded the unexpected result that the number of INS present in the RASS was far below that predicted by early population synthesis models which assumed that a few thousands neutron stars should be detected in the RASS. The results of these observational constraints have been summarized by Neuhäuser & Trümper (1998). We show an updated version of their figure 1 in Fig. 2. At the faint flux end, upper limits on ROSAT INS densities are incompatible with model predictions from Treves & Colpi (1991) and Blaes & Madau (1993) (not shown) but still consistent with the revised models of Madau & Blaes (1994). The most recent large sky area searches (labeled A,B and C in Fig. 2) yield even stronger constraints. The results (A) of Danner et al. (1998) is restricted to dark clouds area and is therefore not directly comparable with model predictions. Constraints labeled B and C cover large unbiased sky areas. (C) results from the identification of very bright soft ROSAT sources with $|b| \geq 20^\circ$ by Thomas et al. (1998). The upper limit shown in (B) is derived from an identification campaign of soft sources over $\sim 1/4$ of the whole sky conducted at ESO (Motch et al. 2000). Optical identification of a total of 116 sources down to a PSPC count rate of 0.17 cts/s yielded only 3 possible cases among which 2 are already known INS. Spectral selection is discussed in Motch et al. (1999).

Contrary to other studies, surveys (B) and (C) assume that accreting INS are intrinsically soft sources and preselect candidates on the basis of ROSAT PSPC hardness ratios. The brightest INS found in the RASS without spectral selection are indeed soft and a soft spectrum is also theoretically expected (e.g. Zampieri et al. 1995). However, the possibility remains that because of the spectral preselection a fraction of the population, for instance INS accreting in very dense medium, escapes the search.

The painstaking optical identification campaigns have yielded the very significant and unexpected result that the number of accreting old INS shining in X-rays is a factor 10 to 1000 below that predicted by population synthesis models. This discrepancy points to a fundamental error in one or more of the model assumptions used. Constraints on an accreting population may be even stronger since; i) the observed LogN-LogS is almost consistent with a young cooling neutron star population only and ii) for none of the INS candidates discovered so far can the accreting model be unambiguously established by the discovery of X-ray variability or the measurement of a negative $\dot{\mathrm{P}}$ for instance. In two cases INS are found in regions of particularly low mean densities contrary to naive expectations ($n \leq 0.4$ and 0.3 cm^{-3} for RX J0720−3125 and RX J1605+3249 respectively). Very low relative velocities of less than 10 km s^{-1} must be assumed to account for the observed luminosities. However, selection effects and ISM patchiness on very small scales may solve this paradox. Finally, accretion should enrich neutron star atmosphere in H and He and could cause a brighter optical continuum than observed (Pavlov et al. 1996).

5. ARE OLD NEUTRON STARS ACCRETING ?

Newly born neutron stars must be spun down efficiently before they can start accreting from the interstellar medium. The evolution of magnetic field with time seems a key parameter as it both determines braking strength during ejector and propeller phases and the minimum period allowing accretion. Treves et al. (1999) argue that for certain values of initial magnetic field and decay time scales, the life time of the ejector phase may be longer than the age of the Galaxy. Colpi et al. (1998) and Livio et al. (1998) also showed that field decay significantly increases the duration of the propeller phase with the consequence that most old neutron stars could still not be able to accrete. Because of the steep dependence of Bondi-Hoyle accretion rate with relative velocity, the velocity distribution of old neutron stars is another key parameter. Early models were based on the work of Narayan & Ostriker (1990). Since then new observations by Lyne & Lorimer (1994) suggest a typical mean velocity at birth of the order of 450 km s^{-1} about twice that of Narayan & Ostriker (1990). These two effects may cooperate to explain the small number of

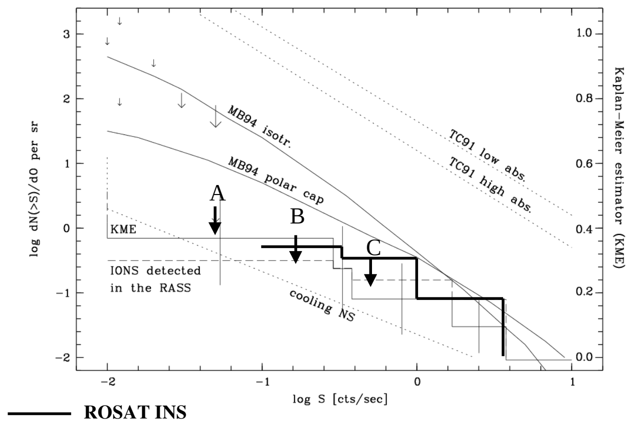

FIGURE 2. LogN-LogS curves for X-ray detected isolated neutron stars after Neuhäuser & Trümper (1998). Lines labelled TC91 amd MB94 represent model predictions from Treves & Colpi (1991) and Madau & Blaes (1994). Thin arrows are upper limits derived from various identification campaigns. The thick curve is the revised INS LogN-LogS curve. Thick arrows marked A,B and C represent upper limits resulting from A) dark clouds (Danner et al. 1998), B) Soft sources on 1/4 of the sky (see text), C) RASS soft sources (Thomas et al. 1998).

X-ray detections.

6. PULSATING SOURCES

Two INS, RX J0720−3125 and possibly RX J0420−5022 have long rotation periods which modulate their X-ray light curve by 20 to 80 %. These spin period are significantly longer than those generally measured in radio pulsars. In the accretion scenario, the spin period yields an estimate of the surface magnetic field which has to be weaker than $\sim 10^{10}$ G to allow for accretion (Haberl et al. 1997). If confirmed, this would clearly point to secular magnetic field decay. Unfortunately, alternative explanations exist. Based on the similarity of spin periods Haberl et al. (1997) proposed that RX J0720−3125 is related to class of anomalous (braking) X-ray pulsars (AXPs). The nature of AXPs itself remains a mystery. Two models often mentioned are i) isolated neutron stars evolving from Thorne-Żytkow objects (van Paradijs et al. 1995) and accreting from a remnant disk and ii) magnetars (Thompson & Duncan 1996). An interpretation in terms of a cooling neutron star faces the difficulty to reconcile thermal and rotational ages. For RX J0720−3125, $T_{bb} = 8\ 10^5$ K implies ages in the range of 1 to 4 10^5 yr (Heyl & Hernquist 1998) whereas the time required to spin down from a short birth period to 8.39 s with dipole radiation is $\sim 1.2\ 10^9\ (B/10^{12}G)^{-2}$ yr. This discrepancy may be solved assuming the star was born with a long period. Alternatively, Heyl & Hernquist (1998) proposed the exciting possibility that RX J0720−3125 is a magnetar with B$\sim 10^{14}$ G, similar to those proposed to explain soft-γ repeaters and AXPs. Because radio emission is quenched by the strong magnetic field magnetars remain undetected by classical radio means. Their birth rate may be $\sim 10\%$ of that of ordinary pulsars (Kouveliotou et al. 1994). Gotthelf & Vasisht (1999) also argue that a large fraction of SNR contains previously unrecognized slowly rotating, radio-quiet and X-ray bright pulsars which could be the natural progenitors of the long period INS discovered by ROSAT. The high magnetic field allows efficient magnetic dipole spin down and its decay provides an additional source of heat which allows magnetars to remain detectable in X-rays over longer times than ordinary pulsars. Consequently, although less numerous than normal pulsars, cooling magnetars may show up in comparable numbers in X-ray surveys.

7. CONCLUSIONS

All optical identification campaigns carried out so far confirm the scarcity of X-ray emitting isolated neutron stars in the ROSAT all sky survey. Clearly, the large population of old galactic neutron stars does not accrete from interstellar medium at the rate predicted by early models, or the accretion energy is re-radiated outside the ROSAT energy band. This unexpected result tells us something fundamental on the kinematics and/or magnetic field evolution of old neutron stars and points to a secular magnetic field decay or a large mean velocity. ROSAT has however discovered a handful of INS sharing as common properties a soft blackbody like X-ray spectrum, absence of luminous radio emission and absence of long term variability. It is not yet proven that any of the 6-7 confirmed INS accretes from ISM. Their small number could be compatible with cooling normal pulsars whose radio beam does not cross the earth or with magnetars evolved from Soft-γ repeaters, AXPs and more generally from the slowly rotating X-ray bright and radio quiet pulsars found in several SNRs. Future observations with VLTs and Chandra/XMM should help to solve the puzzle of the evolutionary status of this population by measuring proper motions, rotation periods and period derivatives which are key parameters to distinguish between young cooling and old accreting INS. Finally these INS should allow the detailed observation of a rather unperturbed neutron star atmosphere and the accurate measurement of fundamental neutron star properties.

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