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The Magnificent Seven: Close-by Cooling Neutron Stars ?

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Abstract.
We model Galactic populations of accreting and cooling isolated neutron stars in the attempt to explore their link with a new class of dim soft X-ray sources revealed by ROSAT. For accretors we follow the magneto-rotational and dynamical evolution in the Galactic potential and a realistic large scale distribution of the interstellar medium is used. Under standard assumptions old neutron stars enter the accretor stage only if their magnetic field exceeds $\approx 10^{11}$–10^{12} G. We predict about 1 source per square degree for fluxes $\approx 10^{-15}$–10^{-16} erg cm^{-2}s^{-1} in the energy range 0.5-2 keV.

Cooling neutron stars are explored within a simpler model of local sources, including however interstellar absorption. They are found to be significantly less abundant at low fluxes, < 0.1 sources per square degree, but dominate over accretors at higher flux levels ($\approx 10^{-12}$–10^{-11} erg cm^{-2}s^{-1}). We suggest that the faint sources observed by ROSAT may be young cooling neutron stars with typical age $\lesssim 10^6$ yrs, if the total number of young neutron stars in the Solar proximity is ~ 10 times higher than inferred from radiopulsars statistics.

1. The Magnificent Seven

Seven soft sources, *The Magnificent Seven*, have been found in ROSAT fields which are most probably associated with isolated radio-quiet NSs. A summary of their main observational properties is reported in the table (see e.g. Neühauser & Trümper 1999, NT99; Motch 2000; Treves et al. 2000, T2000, and references therein; see also Burwitz et al. at this conference).

Table 1. Properties of ROSAT Isolated NS Candidates

Source	PSPC	T_{bb}	N_H	$\log f_X/f_V$	Period
	count s^{-1}	eV	$10^{20}\,\mathrm{cm}^{-2}$		s
MS 0317.7-6647	0.03	200	40	> 1.8	–
RX J0420.0-5022	0.11	57	1.7	> 3.3	22.7
RX J0720.4-3125	1.69	79	1.3	5.3	8.37
RX J0806.4-4132	0.38	78	2.5	> 3.4	–
RBS1223	0.29	118	~ 1	> 4.1	5.2 [a]
RBS1556	0.88	100	< 1	> 3.5	–
RX J185635-3754	3.64	57	2	4.9	–

[a]Hambaryan et al. (2001)

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 (T2000 for a recent review). The ROSAT candidates, although relatively bright (up to ≈ 1 count 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 (T2000). Up to now only two optical counterparts have been identified: RXJ 1856-37, Walter & Matthews (1997), for which a distance estimate of ~ 60 pc has been very recently obtained, and RXJ 0720-31, 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.

A statistical approach, based on the comparison of the predicted and observed source counts may provide useful informations on the nature of these objects. Previous studies derived the $\log N - \log S$ distribution of accretors (Treves & Colpi 1991; Madau & Blaes 1994; Manning et al. 1996) assuming a NSs velocity distribution rich in slow stars ($v \lesssim 100$ km s^{-1}). 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 1998) point, however, to a larger NS mean velocity (T2000). Neühauser & Trümper (NT99) 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, in the light of the latest contributions to the modeling of the evolution of Galactic NSs (Popov et al. 2000, P2000a). A more comprehensive discussion can be found in Popov et al. (2000, P2000b).

2. Accreting isolated neutron stars

An important feature of our approach is the detailed calculation of the magneto-rotational evolution of isolated NSs, calculated as in P2000a (see Lipunov 1992 for the basic concepts), but with slightly revised values for the critical periods governing the Ejector-Propeller and Propeller-Accretor transitions. When the accretor stage is reached, the NS spin period is set equal to the "equilibrium" period (Konenkov & Popov 1997). The form of the Galactic potential is taken as in Paczynski (1990; see also P2000a); some parameters were upgraded in order to fit better solar distance from the Galactic center (see Madau and Blaes 1994). Initially each NS has a circular velocity corresponding to its birthplace, and an additional kick velocity, selected from a Maxwellian distribution, is added. NSs are assumed to be born in the Galactic plane and their birthrate is constant in time and proportional to the the square of the local gas density. The NS magnetic field is taken to follow a log-gaussian distribution. For each evolutionary track we calculate six different magneto-rotational histories, corresponding to different values of the initial magnetic field. Results were then merged and normalized. The total number of NSs in the Galaxy is taken $N_{tot} = 10^9$.

In order to compare theoretical predictions with observations it is useful to produce the $\log N - \log S$ distribution. The brightest accretors in our calculations have luminosities $L \sim 10^{32}\,\mathrm{erg\,s^{-1}}$, but the majority of them cluster around $L = 10^{29} - 10^{30}$ erg s^{-1}. To compare our results with observations of ROSAT sources a conversion factor $0.01\,\mathrm{count\,s^{-1}} = 3\times10^{-13}\mathrm{erg\,cm^{-2}s^{-1}}$ was used (e.g. NT99). We calculate the $\log N - \log S$ distribution for the frequency intergrated flux ($S_{total} = L_{total}/4\pi D^2$, here D is the source distance, $L_{total} = \dot{M}GM/R$) and for the flux in the range 0.5-2 keV. In latter case the spectrum is assumed to be a blackbody and the polar cap radius is calculated with the current values of the magnetic field and accretion rate ($R_{cap} = R_{NS}\sqrt{R_{NS}/R_A}$, where R_A is the Alfven radius). If absorption is negligible, then one expects about 1 source per square degree in the range 0.5-2 keV for limiting fluxes about 10^{-16}–10^{-15} erg cm^{-2} s^{-1}. This should be compared with a total numer of sources presently detected by Chandra of $\sim 10^3$–10^4 (see e.g. Giacconi at this conference). Results are presented in the figure.

3. Cooling neutron stars

Although in principle the evolution of coolers should be computed exactly in the same way as for accretors, they are much more short-lived and hence less numerous. This poses a severe problem about the reliability of our sample which is based on a limited number of evolutionary tracks. This can be avoided exploiting the fact that coolers are a local population of sources. We assume that NSs are uniformly distributed in the disk with half-thickness of 450 pc. The NSs spatial density is a free parameter and can be varied. We used two values, $n_{NS} = 0.33\times10^{-3}\mathrm{pc}^{-3}$ and $n_{NS} = 3.3\times10^{-3}\mathrm{pc}^{-3}$. The first value corresponds to the density adopted by NT99, and comes from radiopulsars statistics. The second one corresponds to $N_{tot} \sim 10^9$ and is suggested by considerations on supernova nucleosynthetic yields (e.g. Arnett et al. 1989). These two values can be compared, for example, with $n_{NS} \sim 1.4 \times 10^{-3}\mathrm{pc}^{-3}$ as derived by Paczynski (1990).

All NSs are assumed to be "standard candles" with $L = 10^{32}$ erg s^{-1} and blackbody spectrum. The duration of the cooling phase was taken to be 10^6 yrs, as suggested by the slow cooling scenario. In the fast cooling model (e.g. Yakovlev et al. 1999) the number of observable coolers should be much smaller, so, potentially, observations of isolated NSs may help in shedding light on their cooling history. The ISM structure is treated in a very simple way: a spherical local Bubble of radius r_l (which can be varied) and density $n = 0.07$ cm^{-3} centered at the Sun and a uniform medium with density $n = 1$ cm^{-3} in the Galactic disc (with scaleheight 450 pc) at larger distances. After the column density N_H is calculated, we compute the source count rate for given luminosity, temperature and column density. Results are shown in the figure.

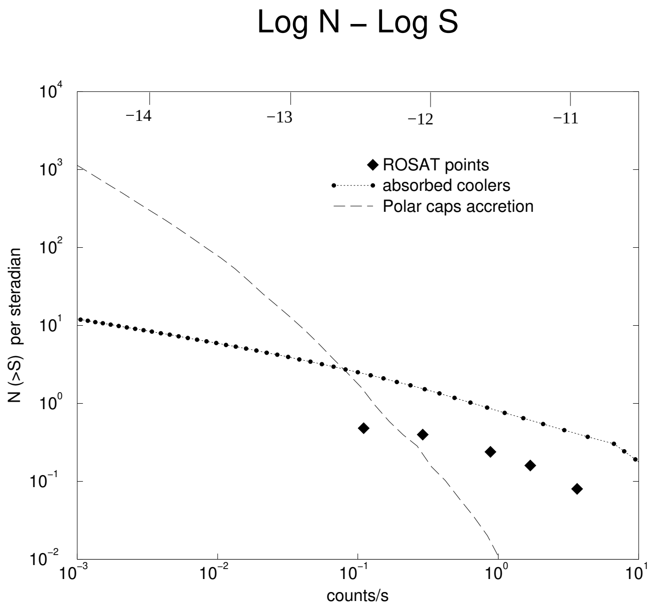

Figure 1. Comparison of the $\log N - \log S$ distributions for accretors and coolers. Top and bottom axes give the flux in erg cm^{-2}s^{-1} and in ROSAT counts/s.

This simple model reproduces a key feature: the flattening of the $\log N$ $-\log S$ distribution outside the Local Bubble, which is important to explain ROSAT data at large fluxes. More sophisticated models with a realistic distribution of both the ISM and the coolers give nearly the same results, and will be presented in a separate paper. In the actual calculation we took $r_l = 140$ pc (equal to the radius of the Local Bubble in our calculations for accretors, see also Sfeir et al. 1999). A clear knee appears due to the effect of absorption. Such strong flattening can help to explain the observed data, if one assumes that the

the vast majority of bright (> 0.1 count s^{-1}) isolated NSs are already identified. The position of the knee can be adjusted varying r_l, n_{NS} and the ISM density; for smaller values of r_l the knee moves to the right, towards higher count rates. By taking a high enough spatial density of NSs these results are able to account for both: i) the number of bright sources, and ii) the flattening of the observed $\log N - \log S$ distribution.

4. Discussion

The task of explaining the observed properties of the seven ROSAT isolated NS candidates within a single model based on standard assumptions is not easy. The ROSAT sources are in fact: i) relatively bright, $\gtrsim 0.1$ count s^{-1}; ii) close, $N_H \sim 10^{20}\mathrm{cm}^{-2}$; iii) soft, $T_{eff} \sim 50 - 100$ eV; iv) slowly rotating, for RX J0720, RX J0420 and RBS1223 the periods are about 5–20 s.

The accretion stage can be reached only if NS magnetic field is $\gtrsim 10^{11}$–10^{12} G. For polar cap accretion the X-ray spectrum is then relatively hard with a typical temperature around 300-400 eV. For them interstellar absorption is not very significant, and we predict about 1 source per square degree for fluxes about 10^{-15}–10^{-16} erg cm^{-2} s^{-1} for energy range 0.5-2 keV. While accretors may indeed represent the bulk of a still undetected low-luminosty population of X-ray sources, it is difficult to reconcile them with the relatively bright ROSAT sources, as shown in the figure. On the contrary, the number distribution of coolers is in agreement with that of the seven isolated NS sources discovered so far, only if the total number of young close-by NSs is a factor ~ 10 larger than what implied by radiopulsar statistics. Taken at face value, this implies that the majority of NSs do not experience an active radiopulsar phase, a major implication which is also supported by other evidences (see e.g. Gotthelf & Vasisht 2000). The interpretation of the observed periods of some of the Magnificent Seven remains problematic and seems to require special conditions on the evolution of the magnetic field and spin.

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