YOUNG COMPACT OBJECTS IN THE SOLAR VICINITY

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We present Log N – Log S distribution for close-by young isolated neutron stars. On the basis of this distribution it is shown that the seven ROSAT isolated neutron stars (if they are young cooling objects) are genetically related to the Gould Belt. We predict, that there are about few tens unidentified close-by young isolated neutron stars in the ROSAT All-Sky Survey. The possibility that these seven peculiar sources contain a neutron star less massive and more magnetized then in ordinary radiopulsars is also discussed. In the aftermath of relatively close recent supernova explosions (1 kpc around the Sun, a few Myrs ago), a few black holes might have been formed, according to the local initial mass function. We thus discuss the possibility of determining approximate positions of close-by isolated black holes using data on runaway stars and simple calculations of binary evolution and disruption.

1 Introduction

Neutron stars (NSs) and black holes (BHs) are among the most interesting astrophysical sources. Usually NSs are observed as radio pulsars or as accreting objects in close binaries. Similarly, stellar mass BHs are observed when they accrete matter from a companion star. Here we focus on much more elusive sources, namely isolated NSs (which may show no radiopulsar activity) and isolated BHs.

An isolated NS can be relatively bright in soft X-rays due to its thermal emission during the first Myrs of its life, when it is still hot ($T \sim 10^6$ K) in the aftermath of the supernova (SN) explosion. Such objects are observed in the Solar proximity and in SN remnants [1]. Older NSs (that is to say those which crossed the deathline in $\approx 10^7$ yr) are not expected to emit appreciable amounts of electromagnetic radiation in any energy band. However, accretion of the interstellar medium (ISM) may make them shine again as soft, faint X-ray sources (see e.g. Treves et al. [2]). Much in the same way, an isolated

BH may be detected if it accretes from the ISM, or, possibly, revealed through microlensing [3].

In this paper we discuss the possible origin of close-by, isolated NSs and present some evidence that the seven radio-quiet, thermally emitting ROSAT sources (the "magnificent seven" [2]) may be characterized by different values of the stellar parameters (mass and magnetic field) with respect to ordinary radiopulsars. We first construct the Log N – Log S distribution for young close-by isolated NSs and compare it with present observations of close-by young isolated NSs of all types. Then we discuss how the alignment of the magnetic and rotation axes, together with the role of fall-back following the supernova event, may help in explaining the observed parameters of NSs. Finally in §3 we discuss how one can estimate an approximate positions of close-by young isolated BHs in the light of their possible detection at X/gamma-rays energies.

2 Isolated neutron stars

In this section we discuss isolated NSs. The material presented here is partly based on the results published in Popov et al. [4]. In addition some recent results are also included [5].

2.1 Origin of close-by isolated NSs

To understand how the local population of isolated NSs originated, we construct their Log N – Log S distribution. The main components of our model are (see [5]): spatial distribution of NS progenitors, NS formation rate, NS cooling history, and a model of interstellar absorption (that is to say the spatial distribution of the ISM). In addition we calculate the dynamical evolution of NSs in the galactic potential. In brief our model can be described in the following way: NSs are born in the Galactic plane and in the Gould Belt (a local compound of stellar associations, see below); at birth they receive a kick velocity; we then follow the evolution of NSs in the Galactic potential; finally, we calculate the ROSAT count rate basing on cooling curves and an assumed model of interstellar absorption.

NSs are considered to be born with a constant rate: 20 NSs per Myr come from the Gould Belt, and 250 NSs per Myr from the Galactic plane (up to a limiting distance of 3 kpc from the Sun) with a uniform distribution. The Gould Belt is modeled as a disk of 500 pc radius with an inclination of 18° with respect to the Galactic plane. Its center is situated at 100 pc from the

Sun in the Galactic anticenter direction. The central region (150 pc in radius) is devoided of newborn NSs (see Pöppel [6] and Torra et al. [7]).

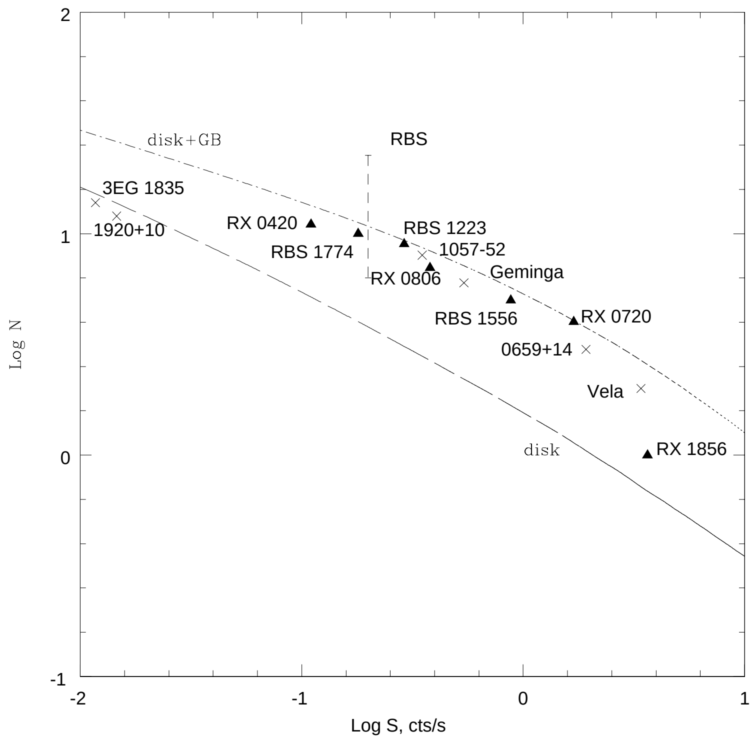

Figure 1: All-sky Log N - Log S distribution. Black triangles – the seven RINSs; crosses – Geminga, "three musketeers", 1929+10 and 3EG J1835. We also show the ROSAT Bright Sources (RBS) limit (Schwope et al. [10]). Upper curve: NSs born in the Gould Belt and in the Galactic disk ($r_{\rm disk} = 3$ kpc, total birth rate 270 $\rm Myr^{-1}$). Lower curve: NSs born only in the Galactic disk ($r_{\rm disk} = 3$ kpc, birth rate 250 $\rm Myr^{-1}$).

To calculate the thermal evolution of NSs we use the data obtained by Sankt-Petersburg group (see Kaminker et al. [8], and the review by Yakovlev et al. [9]). The NS cooling depends on the star mass and we adopt a flat mass spectrum in the range $1.1\,M_\odot < M < 1.8\,M_\odot$. A more standard spectrum with a sharp maximum around 1.35-1.4 $M_\odot$ gives nearly the same result. Cooling curves take into account all neutrino processes but ignore neutron superfluidity in the crust and core since this is not expected to influence the final results significantly. Calculations for each NS are truncated when its temperature drops to 10^5 K; this corresponds to a NS age of 4.25 Myrs for the lightest NSs ($M = 1.1\, M_{\odot}$) or less for more massive objects.

Since we expect the NS to emit most of its luminosity at UV/soft X-ray energies ($\sim 20 - 200$ eV or $T \approx 10^5$–10^6 K) interstellar absorption plays a crucial role as far as the observability of these sources is concerned. Any attempt to estimate the amount of observable cooling isolated NSs using unabsorbed flux *greatly* overestimates their number.

Our main results are presented in Fig. 1 where we compare the Log N – Log S for NSs born in the Gould Belt and the Galactic disk. All curves refer to the whole sky. As can be seen the contribution from NSs born in the disk fails to explain the observed distribution while the inclusion of the objects originating from the Gould Belt *alone* can match the observations. Absorption, the flat geometry of NS initial distribution and the finite extension of the Belt naturally explain the very flat (slope < -1) Log N – Log S distribution.

Our calculations show that there may be at most a few dozens of unidentified close-by isolated NSs in the ROSAT All-Sky Survey (at count rate $>$ 0.015 cts s^{-1}) depending on parameters of the model. Also there may be a few unidentified ROSAT isolated NSs (RINSs) with fluxes $>$ 0.1 cts s^{-1} at low Galactic latitudes (see also Schwope et al. [10]). Most objects should be observed at $|b| < 20^{\circ}$ towards the directions of lower absorption. Some of them can have counterparts among unidentified gamma-ray sources (also possibly connected with the Gould Belt, see Grenier [11]). Identification of these objects can be important for choosing a correct cooling model and for determination of the mass spectrum of NSs.

2.2 Census of close-by young NSs

At present about 20 NSs are known which are younger than 4.25 Myrs and closer than 1 kpc to the Sun (see the Table). They include: the "magnificent seven" (radio-quiet, ROSAT isolated NSs with only thermal emission), Geminga and the Geminga-like object 3EG J1835 (pulsars the beams of which do not intersect the Earth), the "three musketeers" (Vela, PSR 0656+14, PSR 1055-52), PSR 1929+10 and seven young radio pulsars, which have not been detected in X-rays yet.

In addition to the observed sources, we expect about one hundred isolated NSs younger than ~4 Myr inside 1 kpc. These NSs are not detected as radio pulsars, but tens of them can be identified in ROSAT data as dim sources (others are too old to be hot enough). Pulsar beaming can be responsible only for a fraction of these undetected (in the radio) young NSs (about 50-70% of young pulsars are not visible from Earth [12]), and most of RINSs should be really radio silent. This provides strong support to the arguments by Gotthelf and Vasisht [13], that "at least half of the observed young neutron stars follow an evolutionary path quite distinct from that of the Crab pulsar".

2.3 Are RINSs of a different stock ?

An interesting feature of RINSs population is the detection of periods in the $\sim$ 10-20 s range (typical of SGRs/AXPs, i.e. of magnetars) for four objects. Present data allow to exclude any pulsation (down to a few % fraction) for at least one source, RX J1856.5-3754. V. Beskin (2001, private communication) suggested this could be due to the alignment of magnetic and spin axes (see for example Tauris & Manchester [12] for a discussion). Alignment is a process which leads to "period freezing" and a low pulsed fraction.

However in the case of coolers alignment should operate on short timescale, since the star cools down in ≈ 1 Myr. For radio pulsars the timescale of alignment is about 10 Myrs or longer [12], so it seems unlikely that this mechanism is responsible for RINSs distribution of the pulsed fraction, unless one assumes that RINSs form a separate population from normal radio pulsars. To illustrate this let us assume that the alignment timescale is $\tau_{align} \propto (\Omega_0^2 \cos^2\alpha_0\, B_0^2)^{-1}$ (here α_0 and B_0 are initial values of an angle between spin and magnetic axis and of magnetic field). The previous expression comes from magnetodipolar braking supplemented by the condition $\Omega_0 \cos\alpha_0 = \Omega \cos\alpha$. To explain the difference between τ_{align} in RINSs and radio pulsars RINSs need to have a different distribution in B_0 and/or α_0. In this respect RINSs may come from the same population as radiopulsars but are characterized by different average properties, like e.g. higher values of the magnetic field and relatively higher surface temperatures. The latter would imply a lower mass for NSs of the same age.

RINSs are currently thought to be rather highly magnetized objects (in RX J0720.4-3125 the detected spind-down implies $B \sim 2 \times 10^{13}$ G [15]). If this is indeed the case, then one has to explain why their B-field is a factor ~ 10 higher than the average value in radiopulsars ($\sim 2 \times 10^{12}$ G). A possibility is that NSs with higher magnetic fields are hotter. It is known that less massive NSs cools more slowly because direct URCA processes are not effective (see e.g. [9]). This means that among NSs of the same age the lighter are the hotter, so to test our hypotesis we need to show that lighter NSs may support

Table 1: Local ($r < 1$ kpc) population of young (age < 4.25 Myrs) isolated neutron stars.

Object name	Period, s	CR^a, cts/s	$\dot{P}$ $/10^{-15}$	Dist., kpc	Age^b, Myrs	Ref.
RX J1856.5-3754	—	3.64	—	0.117^e	~ 0.5	[2, 14]
RX J0720.4-3125	8.37	1.69	$\sim 30 - 60$	—	—	[2, 15]
RX J1308.6+2127	10.3	0.29	$< 10^4$?	—	—	[2, 16, 17]
RX J1605.3+3249	—	0.88	—	—	—	[2]
RX J0806.4-4123	11.37	0.38	—	—	—	[2, 18]
RX J0420.0-5022	22.7	0.11	—	—	—	[2]
RX J2143.7+0654	—	0.18	—	—	—	[19]
PSR B0633+17	0.237	0.54^d	10.97	0.16^e	0.34	[20]
3EG J1835+5918	—	0.015	—	—	—	[21]
PSR B0833-45	0.089	3.4^d	124.88	0.294^e	0.01	[20, 22, 23]
PSR B0656+14	0.385	1.92^d	55.01	0.762^f	0.11	[20, 23]
PSR B1055-52	0.197	0.35^d	5.83	$\sim 1^c$	0.54	[20, 23]
PSR B1929+10	0.227	0.012^d	1.16	0.33^e	3.1	[20, 23]
PSR J0056+4756	0.472	—	3.57	0.998^f	2.1	[23]
PSR J0454+5543	0.341	—	2.37	0.793^f	2.3	[23]
PSR J1918+1541	0.371	—	2.54	0.684^f	2.3	[23]
PSR J2048-1616	1.962	—	10.96	0.639^f	2.8	[23]
PSR J1848-1952	4.308	—	23.31	0.956^f	2.9	[23]
PSR J0837+0610	1.274	—	6.8	0.722^f	3.0	[23]
PSR J1908+0734	0.212	—	0.82	0.584^f	4.1	[23]

^{a} ROSAT count rate
^{b}) Ages for pulsars are estimated as $P/(2\dot{P})$,
for RX J1856 the estimate of its age comes from kinematical considerations.
^{c}) Distance to PSR B1055-52 is uncertain ($\sim$ 0.9-1.5 kpc)
^{d}) Total count rate (black body + non-thermal)
^{e}) Distances determined through parallactic measurements
^{f}) Distances determined with dispersion measure

a stronger field. Such a correlation arises quite naturally if more massive NSs get their additional mass from fall-back. In this case their magnetic field can be significantly suppressed [24], so more massive NSs should have lower initial magnetic fields. Besides, strong initial magnetic field together with fast rotation can prevent strong fall-back (this is especially possible if the magneto-rotational mechanism of supernova explosion is valid, see [25, 26]). Again this leads to the same correlation between mass and filed strength, i.e. NSs with stronger fields would have lower masses. Also, this picture makes room for long initial spin periods. The study of this (and possible other) correlation in isolated NSs may prove very useful in understanding the correct mechanism of the SN event which gave birth to these objects.

In summarizing §2, we stress that future determination of RINSs parallax and proper motion may help in tracing back their kinematical history and derive their age. It can give a clue to their mass determination basing on cooling curves (see Kaminker et al. [8]). Our results suggest that the fraction of low-mass NSs ($M \lesssim 1.3\ M_\odot$) may not be small. On the other hand there should be room for NSs with $M \gtrsim 1.4 M_\odot$, because otherwise the number of bright objects would be too large.

3 Close-by young isolated black holes

In this section we base on the results published in Popov et al. [4] and Prokhorov and Popov [27].

SNae explosions produce not only NSs, but also BHs. It is commonly accepted that BHs are one order of magnitude less abundant than NSs. This estimate comes from the critical mass for BH formation and follows if one assumes that progenitors more massive than about 35 $M_\odot$ ended as BHs. Having dozens of SNae in the close solar vicinity during the last 10 Myr we can expect several BHs to have formed during the same period in the solar neighborhood.

At present, 56 runaway stars are known within ~ 700 pc from the Sun[28]. Only a few of them result from star-star interactions, so the majority comes from SNae explosions in binary systems. If the above considerations are correct we can expect about 5 BHs formed in about 50 disrupted binaries.

Close-by massive runaway stars give us a chance to calculate the approximate position of close-by young isolated BHs. Among runaway stars the most massive are λ Cep, ζ Pup, HIP 38518 and ξ Per (see Hoogerwerf et al. [28]). Since their mass is $\gtrsim 33\ M_\odot$, the companion (actually the *primary* in the original binary) was even more massive on the main sequence stage. So, the most likely product of the explosion of such a massive star should be a BH.

If the present velocities of runaway stars are known, one can estimate their ages and places of birth. This has been done by Hoogerwerf et al. [28]. To calculate the present position of a BH we have to know the binary parameters, i.e., the masses of stars before the explosion, the BH mass, the eccentricity of the orbit before the explosion, the orbit orientation, and finally the kick velocity of the BH. Some parameters can be inferred from the observation of the secondary star. We can assume a zero kick velocity for BHs and zero orbital eccentricity. Other parameters should be varied within assumed ranges (see details in Prokhorov and Popov [27].

We calculated approximate positions of isolated BHs for the four systems mentioned above and estimated error boxes where these BHs could be found. For ξ Per and ζ Pup we obtained not very large error boxes inside each of which only one unidentified EGRET source is known. We suggest that these objects can be young isolated BHs. For the two other systems (HIP 38518 and λ Cep) the present position of the BH is more uncertain and no definite conclusion on the possible detectability of the collapsed object can be drawn.

4 Conclusions

We have presented evidence that the seven radio-quiet ROSAT isolated NSs discovered so far can be connected with recent SNae explosions in the Gould Belt. These events produced nearby runaway stars and peculiar features in the local ISM including the Local Bubble. The relatively high local spatial density of young NSs is a natural consequence of the large number of massive progenitors in the Belt. The lack of a similar overabundance of active radiopulsars in the Solar vicinity lends further support to the claim that a large fraction ($\sim 50\%$ or more) of young NSs should be radio quiet. According to our results, the ROSAT All Sky Survey may contain about a few tens of unidentified RINSs. Moreover, it is possible that some unidentified RINSs with quite large flux (> 0.1 cts s^{-1}) are still hiding at low Galactic latitudes.

We also propose that massive runaway stars may be used to trace the present position of young close-by isolated BHs. Our calculations allowed to estimate with reasonable accuracy the positions of four such BHs. In two cases the error box is not too large and this may lead in the future to the positive identification of an isolated BH with X/gamma-rays observations.

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