YOUNG COMPACT OBJECTS IN THE SOLAR VICINITY

S. B. POPOV

Sternberg Astronomical Institute
Universitetski pr. 13, Moscow 119992, Russia
E-mail: polar@sai.msu.ru
University of Padova
via Marzolo 8, Padova 35131, Italy

M. E. PROKHOROV

Sternberg Astronomical Institute
Universitetski pr. 13, Moscow 119992, Russia

M. COLPI

University of Milano-Bicocca
Piazza della Scienza 3, Milano 20126, Italy

R. TUROLLA

University of Padova
via Marzolo 8, Padova 35131, Italy

A. TREVES

University dell'Insubria
via Vallegio 11, Como 22100, Italy

We present Log N – Log S distribution for close young isolated neutron stars. On the basis of Log N – Log S distribution it is shown that 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 young isolated neutron stars in the ROSAT All-Sky Survey. In the aftermath of relatively close recent supernova explosions (1 kpc around the Sun, 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 objects. Usually NSs are observed as radio pulsars or as accreting objects in close binaries. Stellar mass BHs normally are observable if they also accrete matter from companions. Here we will focus on isolated NSs (which can show no radio pulsar activity) and BHs.

An isolated NS can be relatively bright (in soft X-rays especially) due to its thermal emission during the first Myr of its life, when it is still hot ($T > 10^6$ K). Such objects are observed in the Solar vicinity and in supernova (SN) remnants[1].

An isolated BH can be found due to accretion of the interstellar medium (NSs can also be found in such a way, see Treves et al.[2]), or due to the microlensing effect[3].

In this paper we will construct Log N — Log S distribution for young close isolated NSs and discuss how one can estimate an approximate positions of close young isolated BHs.

2. Close young neutron stars

In this section we discuss young close isolated NSs. Partly we are based on the results published in Popov et al.[4] and partly we present our recent results[5].

2.1. *Log N — Log S distribution*

Main components of our model are[5]: spatial distribution of NS progenitors, NS formation rate, NS cooling histories, and model of interstellar absorption (i.e. interstellar medium (ISM) distribution). In addition we calculate 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; at birth they receive a kick velocity; then we follow the evolution of NSs in the Galactic potential; while a NS moves in the Galaxy we calculate (with some time step) ROSAT count rate basing on cooling curves and assumed model of interstellar absorption.

We assume that NSs are born in the Galactic disk and in the Gould Belt. NSs are considered to be born with a constant rate. 20 NSs per Myr come from the Gould Belt, and 250 NSs per Myr are uniformly distributed in the Galactic plane with a limiting distance from the Sun 3 kpc. The Gould Belt is modeled as a disk with 500 pc radius and inclination to the

Galactic plane equal to 18°. Center of the disk is situated at 100 pc from the Sun in the Galactic anticenter direction. In the center of the disk there is a hole with a radius 150 pc, where NSs are not born (see a review by Pöppel[6] for detailed description of the Gould Belt, and Torra et al.[7] for a shorter one).

To calculate cooling of NSs we use the data obtained by Sankt-Petersburg group (see recent data in Kaminker et al.[8], and a review in Yakovlev et al.[9]). We use cooling curves for NSs of masses from $1.1\,M_\odot$ to $1.8\,M_\odot$ with a step $0.1\,M_\odot$. Mass spectrum is assumed to be flat ("realistic" spectrum with sharp maximum around 1.35-1.4 solar masses gives nearly the same result). Curves take into account all processes of neutrino emission. Equation of state used in Kaminker et al.[8] was introduced in Prakash et al.[10]. It is *Model I* of Prakash et al. for symmetry energy and compression modulus of saturated nuclear matter, K, is equal to 240 MeV. Maximum NS mass in that model is 1.977 $M_\odot$. Neutron superfluidity in the crust and core is ignored, as far as it does not influenced the final results significantly. Calculations for each NS are truncated when its temperature falls down to 100 000 K; it corresponds to a NS's age 4.25 Myrs for the lightest NSs ($M = 1.1\,M_\odot$) and less for more massive objects.

As far as we expect our NSs to emit most of their luminosity at soft energies $\sim 20 - 200$ eV (which corresponds to temperatures about 10^5–10^6 K) we have to take into account interstellar absorption. Absorption is a very important feature of our model. Any attempts to estimate the amount of observable cooling isolated NSs using unabsorbed flux *greatly* overestimate this number.

Main results are presented in the Fig. 1. We present a curve for NSs born both in the Gould Belt and the Galactic disk and a curve only for the disk to show the relative importance of the Gould Belt. All curves are referring for the whole sky.

As can be seen the Gould Belt *alone* can explain all observed points. Absorption and flat geometry of NSs distribution naturally explain very flat (< -1) Log N – Log S.

Our calculations show, that there are about few dozens of unidentified close isolated NSs in ROSAT All-Sky Survey (> 0.015 cts s^{-1}) depending on parameters of the model, also there can be few unidentified ROSAT isolated NSs (RINSs) with fluxes > 0.1 cts s^{-1} at low Galactic latitudes (see also Schwope et al.[11]). Most of objects should be observed at $\sim \pm\, 20°$ from the Galactic plane towards the directions of lower absorption. Some of them can have counterparts among unidentified gamma-ray sources (also connected with the Gould Belt, see Grenier[12]). Identification of these objects can be important for choosing a correct cooling model and for determination of mass spectrum of NSs.

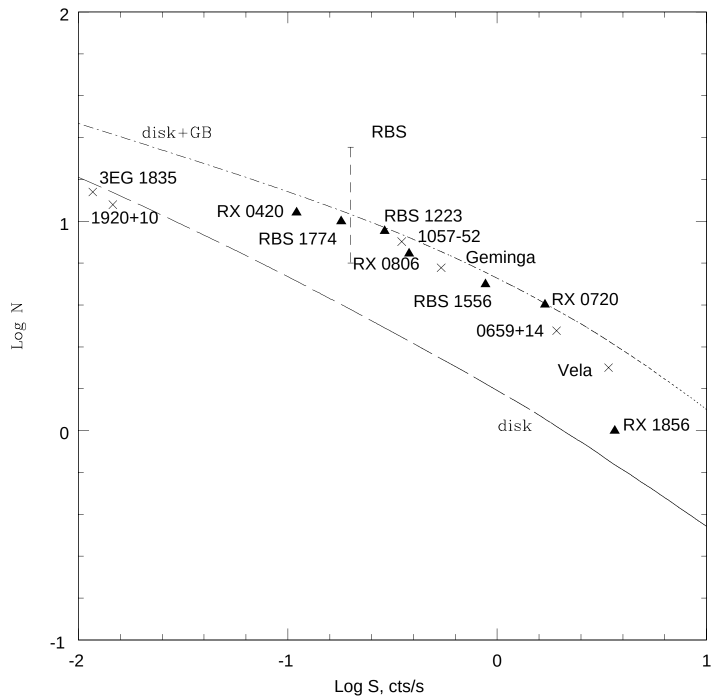

Figure 1. All-sky Log N - Log S distribution. Black triangles — seven RINSs. Crosses — Geminga, "three musketeers", 1929+10 and 3EG J1835. We also show the ROSAT Bright Sources (RBS) limit (Schwope et al.[11]). Upper curve: NSs born in the Gould Belt and in the Galactic disk ($r_{\rm disk} = 3$ kpc, total birth rate 270 Myr^{-1}). Lower curve: only NSs born at the Galactic disk ($r_{\rm disk} = 3$ kpc, birth rate 250 Myr^{-1}).

2.2. *Census of close young isolated neutron stars of different types*

At the present moment it is known about 20 NSs satisfying the following criteria: age less than 4.25 Myrs, distance from the Sun less than 1 kpc (see the Table). It includes: the "magnificent seventh" (seven RINSs), Geminga and the Geminga-like object 3EG J1835, "three musketeers" (Vela, 0656+14, 1055-52), 1929+10 and seven young radio pulsars, which are not detected in X-rays.

We see, that among local young isolated NSs we have normal radio pulsars, pulsars beams of which do not pass the Earth (Geminga and probably 3EG J1835), and RINSs. Also we can expect, that around us (inside 1 kpc) there are about one hundred of isolated NSs younger than ∼4 Myr (some of NSs born inside 1 kpc of course can leave this volume in several Myrs). 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). The beaming effect can be responsible only for part of these undetected (as radio pulsars) young NSs (about 50-70% of young pulsars are not visible from Earth[13]), and most of RINSs should be really radio silent (it is difficult to construct a model in which one observes X-ray pulsations, pure black body spectrum and no signs of radio emission from a close off-beam pulsar, also one has to take into account long periods of four RINSs). It gives strong support to the arguments by Gotthelf and Vasisht[14], that "at least half of the observed young neutron stars follow an evolutionary path quite distinct from that of the Crab pulsar".

2.3. *Alignment*

An interesting feature of RINSs population is an existence of periods about 5-20 seconds (typical for magnetars) for four objects and their absence for the rest three.

Vasily Beskin (2001, private communication) suggested, that it can happen due to alignment of magnetic and spin axis (see for example Tauris, Manchester[13] for a recent discussion on alignment). Alignment is a process which also leads to a "period freezing" and low pulsation fraction (see Haberl, Zavlin[18] for the data on pulsation fraction in RINSs).

However in the case of coolers alignment should operate on short timescale — the timescale of NS cooling ($\sim$ 1 Myr). As far as for radio pulsars timescale of alignment is about 10 Myrs or longercitetm, we think, that it is unlikely that this mechanism is responsible for RINSs distribution over pulsation fraction, otherwise one has to assume that RINSs form a population separate from normal radio pulsars. For example, if we assume, that alignment timescale is $\propto (\Omega_0^2 \cos^2\alpha_0\, B_0^2)^{-1}$ (it comes from magnetodipole spin-down and condition $\Omega_0 \cos\alpha_0 = \Omega \cos\alpha$; also there can be other assumptions about alignment process, but at the moment there is no generally accepted model), then we have to assume that RINSs have dif-

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	2,15
RX J0720.4-3125	8.37	1.69	$\sim 30 - 60$	—	—	2,16
RX J1308.6+2127	5.15	0.29	$\sim 10^4$	—	—	2,17
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

ferent (from radio pulsars) distribution in B_0 or/and α_0, and the observed situation is just a selection effect. For example they can be a sample selected by relatively high surface temperatures, which for young NSs means by low masses.

2.4. *Possible correlation between initial magnetic fields and masses of neutron stars*

If any part of RINSs (with or without observed pulsations) is explained by high magnetic field, then one has to explain why the fraction of magnetars is so high ($\sim 50\%$). It can be explained as a selection effect if NSs with higher magnetic fields are hotter. It can be so, if they have (on average) lower masses (below some value, which is about 1.3 $M_{\odot}$ but depends on the equation of state, direct URCA process are not allowed, and NS cooling is much slower).

The possible correlation can be explained if more massive NSs get their additional masses in the process of fall-back. In that case their magnetic field can be significantly suppressed[24], so more massive NSs should have lower initial magnetic fields.

Also there is a question if the matter is swept out, or it is accumulated close to the magnetospheric boundary, and then accreted by the compact object. But numerical estimates[25,26] suggest, that significant part of matter is swept from the propelling NS.

Vice versa, strong initial magnetic field together with fast rotation can prevent strong fall-back (it is especially possible if magneto-rotational mechanism of supernova explosion is valid, see Bisnovatyi-Kogan[27] and Prokhorov, Postnov[28]), and may be it can also lead to long initial spin periods.

Different crust thickness and temperature of NSs of different masses can give additional correlations between mass and magnetic field, the same can be said about different properties at cores of NSs of different masses (for example, deconfinement in central parts of massive NSs[29]).

Correlations should be different in different scenarios of SN explosion. Study of such correlations can give additional possibilities to select a correct scenario.

To summarize, we can expect correlations between magnetic fields and masses of NSs, and observations of RINSs can be of great importance here. Future determination of RINSs parallaxies and proper motions can help to reconstruct their kinematical history and derive their ages. 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 massive NSs (M <1.3-1.4 $M_{\odot}$) can not be small, but on the other hand there should be a room for massive NSs, because other wise we overpredict the number of bright objects.

3. Close young isolated black holes

In this section we are based on the results published in Popov et al.[4] and Prokhorov, Popov[30].

SNae explosions produce not only NSs, but also BHs. Usually it is accepted that BHs are one order of magnitude less abundant than NSs. This estimate comes from the critical mass for BH formation. If this mass is about 35 $M_\odot$ then the fraction of BHs is about 10%. 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.

In 700 pc around the Sun 56 runaway stars are known[31]. Only few of them can result from star-star interactions. Others are products of SNae explosions in binary systems. If the above considerations are correct we can expect about 5 BHs formed in about 50 disrupted binaries.

Close massive runaway stars give us a chance to calculate an approximate positions of close-by young isolated BHs. Among runaway stars we can distinguish the most massive: λ Cep, ζ Pup, HIP 38518 and ξ Per (see Hoogerwerf et al.[31]). Their masses are larger than $\sim 33\ M_\odot$. It means, that 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.[31]. 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 velovity for BHs and zero orbital eccentricity. Other parameters should be varied within assumed ranges (see details in Prokhorov, Popov[30].

We calculated approximate positions of isolated BHs for four systems mentioned above and estimated erroe boxes where these BHs can be found. For ξ Per and ζ Pup we obtained not very big error boxes inside each of which only one unidentified EGRET source is known. We suggest, that these objects can be young isolated BHs. For two other systems (HIP 38518 and λ Cep) error boxes of the present day BH localization are very large (even with our assumption of zero kick velocity).

4. Conclusions

We conclude that the seven radio-quiet ROSAT isolated NSs can be connected with recent SNae explosions, which produced nearby runaway stars and peculiar features in the local ISM including the Local Bubble. Relatively high local spatial density of young NSs is due to large number of massive progenitors in the Belt. As far as there are few young radio pulsars in the Solar vicinity many (about 1/2 or more) of isolated NSs should be radio quiet. We find that in ROSAT All-Sky Survey it can be about few tens of unidentified RINSs. Also there can be few unidentified RINSs at fluxes > 0.1 cts s^{-1} at low Galactic latitudes.

Massive runaway stars can be used to estimate approximate positions of young close-by isolated BHs. We do the correspondent calculations and estimate present day positions of four BHs. For two of them error boxes are not too large.

5. Acknowledgments

We want to thank D.G. Yakovlev for the data on cooling curves and comments on them, and V.S. Beskin, Matteo Chieregato, Andrea Possenti and Luca Zampieri for discussions.

The work of S.P. was supported by the RFBR grant 02-02-06663. The work of M.P. — by RFBR 01-15-99310.

S.P. thanks Universities dell'Insubria, Milano-Bicocca, Padova and the Organizers of the School for hospitality.

References

1. W. Becker and G. Pavlov, in: "The Century of Space Science", eds. J. Bleeker, J. Geiss and M. Huber, Kluwer Academic Publishers (in press) (astro-ph/0208356) (2002).
2. A. Treves, R. Turolla, S. Zane and M. Colpi, *PASP* **112**, 297 (2000).
3. E. Agol, M. Kamionkowski, L.V.E. Koopmans and R.D. Blandford, *ApJ* **576**, L131 (2002).
4. S.B. Popov, M.E. Prokhorov, M. Colpi, A. Treves and R. Turolla, *Gravitation & Cosmology* (in press) (astro-ph/0201030) (2002).
5. S.B. Popov, M. Colpi, M.E. Prokhorov, A. Treves and R. Turolla, in preparation.
6. W. Pöppel, *Fund. Cosm. Phys.* **18**, 1 (1997).
7. J. Torra, D. Fernández and F. Figueras, *A&A* **359**, 82 (2000).
8. A.D. Kaminker, D.G. Yakovlev and Y.O. Gnedin, *A&A* **383**, 1076 (2002).
9. D.G. Yakovlev, K.P. Levenfish and Yu.A. Shibanov, *Physics-Uspekhi* **42**, 737 (1999).

10. M. Prakash, T.L. Ainsworth and J.M. Lattimer, *Phys. Rev. Lett.* **61**, 2518 (1988).
11. A.D. Schwope, G. Hasinger, R. Schwarz, F. Haberl and M. Schmidt, *A&A* **341**, L51 (1999).
12. I.A. Grenier, *A&A* **364**, L93 (2000).
13. T.M. Tauris and R.N. Manchester, *MNRAS* **298**, 625 (1998).
14. E.V. Gotthelf and G. Vasisht, in: Proceedings of IAU Coll. 177 "Pulsar astronomy - 2000 and beyond", eds. M. Kramer, N. Wex, and N. Wielibinski, ASP Conf. Series **202**, 699 (2000).
15. D.L. Kaplan, M.H. van Kerkwijk and J. Anderson, *ApJ* **571**, 447 (2002).
16. S. Zane, F. Haberl, M. Cropper, V. Zavlin, D. Lumb, S. Sembay and C. Motch, *MNRAS* **334**, 345 (2002).
17. V. Hambaryan, G. Hasinger, A.D. Schwope and N.S. Schulz, *A&A* **381**, 98 (2001).
18. F. Haberl and V.E. Zavlin, *A&A* **391**, 571 (2002).
19. L. Zampieri et al., *A&A* **378**, L5 (2001).
20. W. Becker and J. Trümper, *A&A* **326**, 682 (1997).
21. N. Mirabal and J.P. Halpern, *ApJ* **547**, L137 (2001).
22. G.G. Pavlov, V.E. Zavlin, D. Sanwal, V. Burwitz, and G.P. Garmire, *ApJ* **552**, L129 (2001).
23. ATNF Pulsar Catalogue, **http://wwwatnf.atnf.csiro.au/research/pulsar/catalogue/**
24. D. Page, U. Geppert and T. Zannias, *Mem. Soc. Astr. It.* **69**, 1037
25. Yu.M. Toropin, O.D. Toropina, V.V. Savelyev, M.M. Romanova, V.M. Chechetkin and R.V.E. Lovelace, *ApJ* **517**, 906 (1999).
26. M.M. Romanova, O.D. Toropina, Yu.M. Toropin and R.V.E. Lovelace, *ApJ* (in press) (astro-ph/0209548) (2003).
27. G.S. Bisnovatyi-Kogan, *AZh* **14**, 652 (1970).
28. M.E. Prokhorov and K.A. Postnov, *Odessa Astr. Publ.* **14**, 78 (astro-ph/0110176) (2001).
29. A. Sedrakian and D. Blaschke, *Astrofizika* **45**, 203 (hep-ph/0205107) (2002).
30. M.E. Prokhorov and S.B. Popov, *Astronomy Letters* **28**, 542 (2002).
31. R. Hoogerwerf, J.H.J. de Bruijne and P.T. de Zeeuw, *A&A* **365**, 49 (2001).