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Age-Distance diagram for close-by young neutron stars

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Abstract. An age–distance diagram for close-by young isolated neutron stars of different types is introduced and discussed. It is shown that such a diagram can be a useful tool for studying of populations of sources if their detectability strongly depends on age and distance.

Key words. stars: neutron – stars: evolution – pulsars: general

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1. Introduction

There is a growing evidence that young neutron stars (NSs) can have a wide diversity of parameters and correspondently can manifest themselves as sources with different properties: normal radio pulsars (PSRs), soft-gamma repeaters (SGRs), anomalous X-ray pulsars (AXPs), radioquiet X-ray bright central compact objects in supernova remnants (CCOs in SNRs), γ-ray (for example EGRET) sources, radioquiet dim X-ray sources (like the Magnificent Seven, hereafter M7). In addition to all these stocks of sources there can be young NSs which are so dim in any band to avoid detection with present day instrumentation.

If a NS is young enough ($\lesssim 10^5$–10^6 years) then as a "bonus" we have a possibility to detect its thermal emission. Such observations are of great importance because studying of the thermal evolution is one of a very few chances "to look inside" a NS as far as the thermal evolution strongly depends on the internal structure. Also sometimes thermal emission is the only way to detect a young NS.

Fortunately the solar vicinity ($\lesssim$ 0.5–1 kpc) is enriched with young ($\lesssim$ few Myr) NSs due to the Gould Belt which makes studying of young NSs easier. In particular NSs from the Gould Belt can be responsible for a significant part of unidentified EGRET sources (see Grenier 2000, Gehrels et al. 2000) and for the M7 (Popov et al. 2003).

Young close-by NSs are now actively studied both from observational and theoretical sides (see recent reviews in Kaspi et al. 2004, Popov & Turolla 2004 and references there in). In this short note I introduce and discuss a simple age-distance diagram, which can help to understand properties of the local population of young NSs.

2. Age-distance diagrams

If we are speaking about observations of thermal emission of young cooling NSs then most of their properties depend on their age, and their detectability in X-rays of course strongly depends on distance (not only because of flux dilution, but also because of strong interstellar absorption of soft X-rays). In that sense it is useful to plot an age-distance diagram (ADD) for these objects.

There are several reasons for introduction of ADDs. At first an ADD easily illustrates distributions of sources in age and distance. Then it is possible to plot "expectation lines" for abundance of sources of different types and compare them with data. Finally since observability of sources depends mainly on their ages and distances, it is possible to illustrate observational limits.

In the following figures ADDs for close-by young NSs are presented. These objects can be observed in soft X-rays due to their thermal emission. The thermal evolution strongly depends on mass. According to different models (see Kaminker et al. 2002, Blaschke et al. 2004 and references there in) a NS with a mass ~ 1.3–$1.4\,M_\odot$ remains hot ($T \sim$ (0.5–

1) 10^6 K, or equivalently $\sim$ 50–100 eV) up to $\sim$ 0.5–1 Myr. It corresponds to a luminosity $\sim 10^{32}$ erg s^{-1}. Usually NSs with low masses (1–1.3 $M_\odot$) cool down slower, with higher masses – faster.

To plot an ADD it is necessary to fix maximal values for age and distance for selection of sources. As a limiting age for selection of observed sources I choose 4.25 Myrs. This is the time after which even a low-mass NSs cools down to $\sim 10^5$ K and becomes nearly undetectable in X-rays (see Kaminker et al. 2002, Popov et al. 2003). A limiting distance is taken to be equal to 1 kpc (because of absorption it is difficult to detect in X-rays an isolated NS at larger distance). In the table 1 in Popov et al. (2003) there are 20 sources of different nature which are supposed to be young close-by NSs (age $<$ 4.25 Myr, distance $<$ 1 kpc): the M7, Geminga and the geminga-like source RX J1836.2+5925, four PSRs with detected thermal emission (Vela, PSR 0656+14, PSR 1055-52, PSR 1929+10[1]), and seven PSRs without detection of thermal emission. Not for all of these sources there are good estimates of ages and/or distances (especially for the M7). In the figures there are data points for 13 objects for which such estimates exist (distance to PSR B1055-52 is uncertain, and we accept it to be 1 kpc). Note, that there are also two PSRs with distance $<$1 kpc and with ages in between 4.25 and 5 Myr (PSR B0823+26, PSR B0943+10) and PSR J0834-60 with distance 0.49 kpc and unknown age. These three objects are not included into the figures. Also PSR B1822-09 with age 0.23 Myr and distance 1 kpc is not plotted.

Two types of objects are distinguished on the graphs: detected and undetected due to thermal X-ray emission (remember about seven additional sources – six from the M7 and one geminga-like object – for which there are no definite determinations of age or/and distance).

I start with a simple toy-model plot, then a realistic initial distribution of NSs is considered, and finally dynamical effects are taken into account.

In the first figure a simplified example of an ADD is shown. This example is very illustrative as far as all dependences in the limits of small an large distances are clear. Here it is assumed that the Sun is at the center of a spherically symmetric structure with R_b = 300 pc (in some sense it mimics the Gould Belt). Then at larger distances NSs are considered to be born in a disk. NS formation rate in *"The Belt"* is assumed to be $\dot{n}_1$ =235 Myr^{-1} kpc^{-3} (which corresponds to 26–27 NSs in one Myr up to R_b). In the disk the same quantity is $\dot{n}_2$ =10 Myr^{-1} kpc^{-2} (280 NSs in one Myr up to 3 kpc). This value are more or less equal to the one used in Popov et al. (2004). So at small distances ($R < R_\mathrm{b}$) number of sources grows nearly as the cube of distance, and at large distances – as the square.

[1] It should be mentioned, that soft X-ray emission of PSR 1929+10 can be due to polar caps or due to non-thermal mechanism

The solid line (the lower one) corresponds to one object of given age at a specified distance. The line is calculated as:

$$t = \frac{1}{4/3\pi \dot{n}_1 R^3},\ R < 300\,\mathrm{pc};$$

$$t = \frac{1}{4/3\pi \dot{n}_1 R_b^3 + \pi \dot{n}_2 (R - R_b)^2},\ R > 300\,\mathrm{pc}.$$

Here t is in Myrs, R – in kpc.

The dotted line corresponds to 13 objects (there are 13 sources shown as symbols). Three lines (dashed, dot-dashed and dot-dot-dashed) corresponds to one sources from one of the three mass ranges: 1.05–1.3 $M_\odot$ (73% of all NSs), 1.3–1.55 (26%), 1.55–1.8 (1%). They were obtained just by shifting the solid line along the vertical (age) axis for factors ∼1.37, ∼3.85, 100. These values correspond to the NS mass spectrum which was used in Popov et al. (2004). All five described lines have the same shape which is better seen in the top one (dot-dot-dashed).

In addition I add a "visibility" line (the solid one in the middle of the plot). The idea is to show a maximal distance for a given age (or vice versa a maximal age for a given distance) at which a hot (i.e. low-mass) NS can be detected. The cooling curve is taken from Kaminker et al. (2002) for $M = 1$–$1.3\,M_\odot$ (in the model of these authors cooling of NSs with $M \lesssim 1.35\,M_\odot$ is nearly mass-independent). Such curves were used for example in (Popov et al. 2003). As soon as a cooling curve is fixed then the age determines the luminosity of the object. The limiting unabsorbed flux is assumed to be 10^{-12} erg cm^{-2} s^{-1}. According to WebPIMMS[2] it corresponds to ~ 0.01 ROSAT PSPS counts per second for $N_H = 10^{21}$ cm^{-2} and a blackbody spectrum with $T = 90$ eV, or to ~ 0.1 ROSAT PSPS counts per second for $N_H = 10^{20}$ cm^{-2} and a blackbody spectrum with $T = 50$ eV. The latter values corresponds to the dimmest source among the M7 – RX J0420.0-5022; the former to possibly detectable hot far away objects. Without any doubt such simple approach underestimates absorption at large distances. So the age at which a NS is still observable is overestimated, but for distances $\lesssim 1$ kpc and ages $\lesssim 1$ Myr it should not be a dramatic effect.

In the figure 2 I present the same plot as in figure 1 but for a more realistic model. Here NS formation rate is taken from the numerical model used in Popov et al. (2004). NSs were not followed during their dynamical evolution, so numbers correspond to initial values (this is equivalent to zero kicks and progenitor velocities). In 4.3 Myr in 1 kpc around the Sun about 200 NSs are expected to be born.

In the final picture an ADD with an inclusion of the dynamical evolution of NSs is shown. I.e. here NSs' movements in the Galactic potential are accurately calculated (all procedures are the same as in Popov et al. 2004, kick velocities are taken from

[2] http://heasarc.gsfc.nasa.gov/docs/corp/tools.html

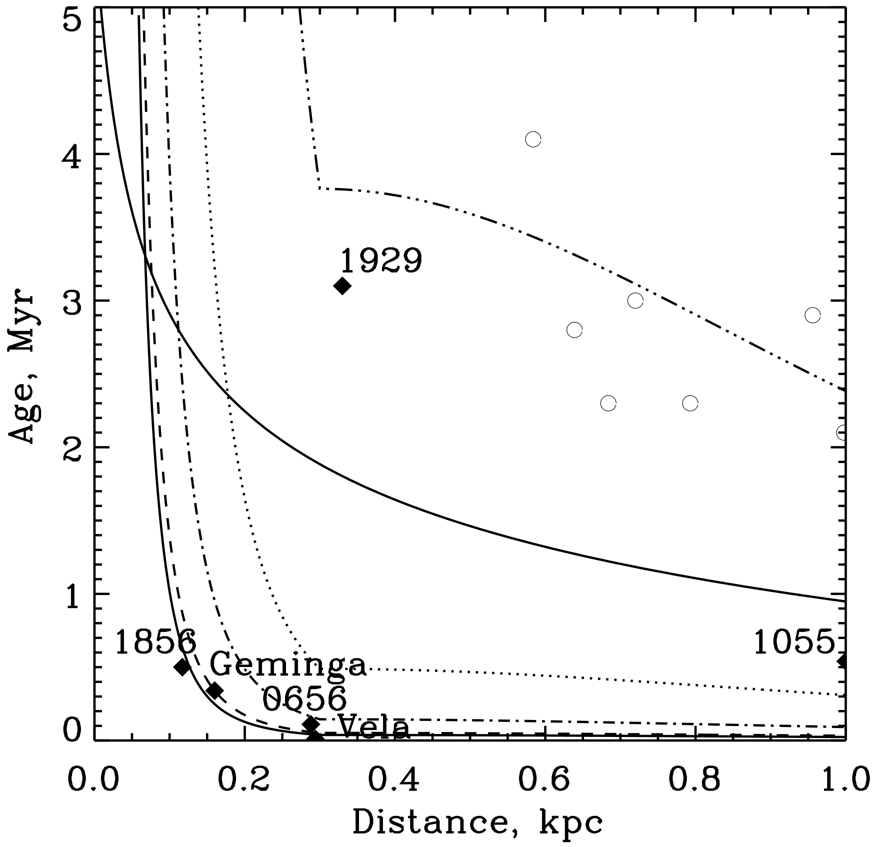

Fig. 1. Distance-age diagram for a toy-model. Filled symbols – sources detected in X-rays, empty – non-detected.

Arzoumanian et al. 2002). For clearity in the last figure the names of objects are not plotted. Five solid lines are plotted for 1, 4 (it should be close to the line for NSs in the mass range 1.3–1.55 $M_{\odot}$, see above), 13, 20 and 100 sources for comparison with the previous figures. Obviously all lines are shifted to the left in comparison with fig.2 because sources are leaving the volume presented on the graphs ($R < 1$ kpc). Shifts are more pronounced for large expected numbers of NSs. The dotted line represents the "visibility" line.

3. Discussion and conclusions

The fact that the line for 20 sources lies below ~1/2 of the observed points tells us that according to our model not all NSs are observed. For example, at R=1 kpc we expect to see 20 sources with ages ~0.5 Myr, but in reality we observe 20 sources with age <4.25 Myr. It means that for constant NS formation rate we see only about 10% of them. One has to bear in mind that for seven sources ages or/and distances are unknown, but they are suspected to be young and close, this is why here we discuss 20 and not 13 sources. Their inclusion or exclusion changes our conclusions quantitatively, but not

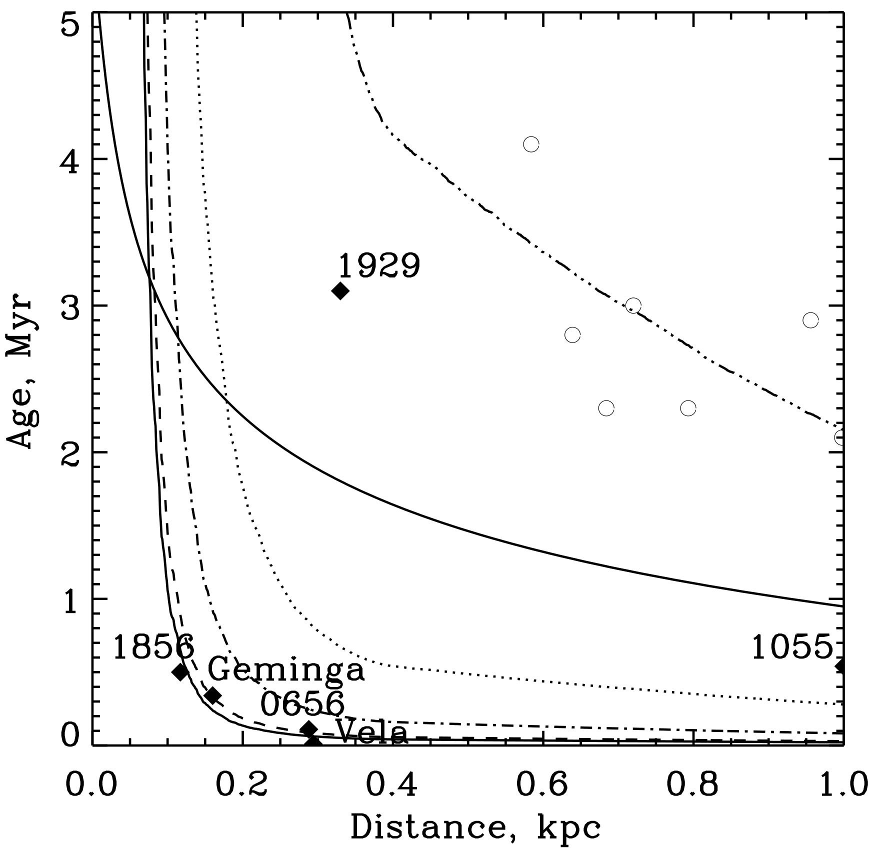

Fig. 2. Age-distance diagram for close-by young NSs with realistic birth rate and initial distribution, but without dynamical effects.

qualitatively. Six of the M7 sources which are not plotted on the graphs due to lack of good distance measurement should populate the left bottom corner of the graphs, since according to models of NS thermal evolution (see for example Kaminker et al. 2002, Blaschke et al. 2004) their ages are expected to be $\lesssim 1$ Myr, and their distances should be $\lesssim 500$ pc. NSs can easily escape detection as *coolers* simply because they cooled down in ~ 1 Myr. A fraction of PSR can be undetected due to beaming (however, they may be observed as EGRET sources).

PSR B1929+10 lies above the "visibility line". However it is unclear if X-ray emission of this faint (0.012 ROSAT cts s^{-1}) source is due to non-thermal mechanism or not (Becker & Trümper 1997). Larson & Link (1999) suggested an additional heating for this PSR due to some internal mechanisms. Now this object is not widely accepted as a *cooler* and usually it is not plotted on the $T-t$ graphs with cooling curves (see also recent papers by Zavlin & Pavlov 2004 and Becker et al. (2004) where the authors briefly comment on that source).

Surprisingly fluctuations in the part of the plot with small number of NSs are not large. Probably we see nearly all low-massive NSs with ages $\lesssim 1$ Myr at $R \lesssim 300$–400 pc.

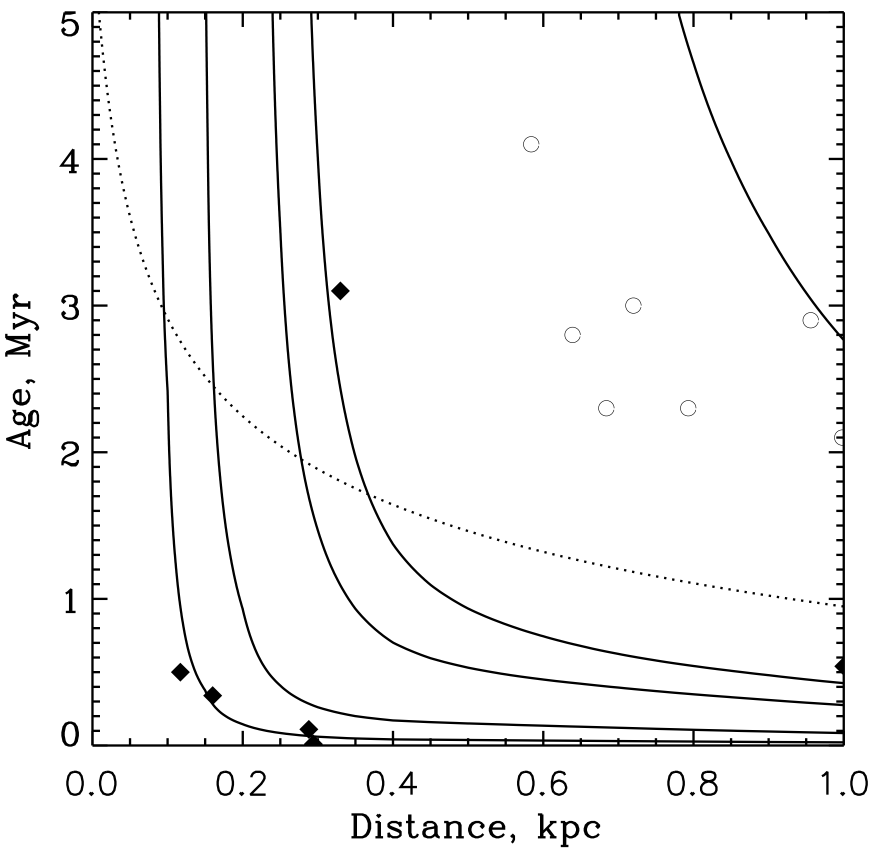

Fig. 3. Age-distance diagram with dynamical effects. Solid lines (from bottom to the top) corresponds to 1, 4, 13, 20 and 100 sources. The dotted line is the "visibility" line (see the text).

It should be noted that we are very lucky to have such a young and close object as the Vela pulsar. If one believes in the mass spectrum with small fraction of NSs with $M > 1.5\,M_\odot$ then inevitably one has to conclude that Vela cannot be a massive NS. It can be important in selection of cooling models (see Blaschke et al. 2004). If in a model Vela is explained only by a cooling curve for $M > 1.5\,M_\odot$ then the model may be questionable. In fact, having such a young and massive NS so close is very improbable. Similar conclusion can be made for Geminga and PSR 0656+14.

There is a deficit of sources below the "visibility" line. These sources could be already detected as dim X-ray sources by ROSAT but were not identified as isolated NSs. The limit for the number of isolated NSs from the BSC (Bright Source Catalogue) is about 100 sources at ROSAT count rate >0.05 cts s^{-1} (see Rutledge et al. 2003). However we do not expect to see that many young isolated NSs due to their thermal emission. An expected number of *coolers* observable by ROSAT is about 40 objects with ages $\lesssim 1$ Myr inside $R \lesssim 0.5$–1 kpc (see the "visibility" line in the fig.3 in comparison with the line for 20 sources, for example). As it was shown by Popov et al. (2004) most of unidentified *coolers* in ROSAT data are expected to be located at low galactic latitudes in crowded regions.

In the figure 2 and especially in the figure 3 in comparison with the first graph it is visible that lines rise at small distance faster than the third power of distance. There are two reasons for such behaviour. The first one is related to the initial spatial distribution of NSs (or in another way to the accepted distribution of progenitors, see details in Popov et al 2004): no NSs are supposed to born in $\sim$ 50–100 pc around the Sun (depending on direction). The second reason (which is the main one) is connected with high spatial velocities of NSs. With $V \sim 300$ km s $^{-1}$ a NS makes 300 pc in 10^6 years. As a result the number of NSs with ages $\gtrsim 1$ Myr in the solar proximity is decreased.

According to the classical picture all NSs were assumed to be born as PSRs more or less similar to Crab. Depending on the initial parameters they were assumed to be active for $\sim 10^7$ yrs. In the last years this picture was significantly changed Gotthelf & Vasisht (2000). Without any doubts we see a deficit of young PSRs in the solar vicinity in comparison with an expected value of young NSs from the Gould Belt and the beaming factor cannot be the only reason for this deficit. This deficit can be explained if one assumes that a significant part of NSs do not pass through the radio pulsar stage or that this stage is extremely short for them. Of course fluctuations (in time and space) of NS production rate can be important as far as statistics is not that high.

Comparison of fig.2 and 3 shows that influence of dynamics is important mostly for old or far away stars. Since the kick velocity distribution is bimodal with 40% of "low-velocity" ($\lesssim 300$ km s^{-1}) and 60% of high-velocity ($\gtrsim 300$ km s^{-1}) NSs (Arzoumanian et al. 2002), the role of the dynamical evolution is more important for objects from the high-velocity peak of the distribution. Obviously in that case we expect to see more middle-age (1–3 Myr) objects from the low-velocity peak closer to us: among 20 objects only PSR B2045-16 with transverse velocity $V_{\rm t} \sim 350$ km s $^{-1}$ belongs to the high-velocity peak (for several objects velocity is unknown). It is unclear if such effect can lead to any observational consequencies. It is quite possible that compact stars populating the two parts of the velocity distribution can have different properties. Even in the absence of correlations of some parameters with velocity *inside* each part of the kick distribution it can exist between the two parts (see Bombaci & Popov for a more detailed discussion). For example as far as kick is definitely connected with the physics of a SN explosion, then if a significant part of mass is obtained by a NS due to fall-back, we can expect if not a mass-velocity correlation then at least a difference in an average mass in the low- and high-velocity peaks (see Popov et al. 2002 on correlations with mass). As far as the cooling history is determined by a NS mass, then a correlation between temperature (for a given age) and velocity can be expected.

I conclude that an ADD can be a useful tool for illustration of the properties of close-by NSs. Its modifications can be applied to other types of sources. For example an addition of the third axis (for p or $\dot{p}$ for example) can be useful in discussing the population of radiopulsars.

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