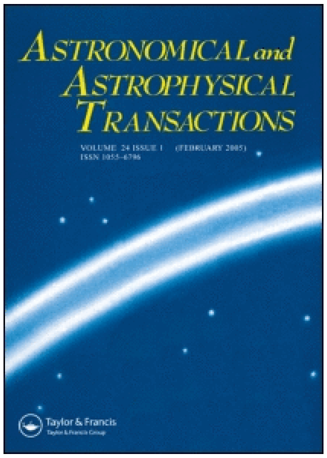

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THE EVOLUTION OF SINGLE PULSARS ON A P–$\dot{P}$ DIAGRAM

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The evolution of single galactic field pulsars on a P–$\dot{P}$ diagram is considered. An unavoidable increase in the mean value of braking indices n averaged over many years, for pulsars with characteristic times τ in the range $4.5 < \log\tau < 5.5$, of up to 5 and more is shown. Some candidates for such pulsars are suggested. The increase in deviation between the real lifetimes t, of pulsars and their characteristic times τ, with increase in τ, is explained. The important result of this work is that the origin of single pulsars with a relatively low magnetic field $B < 3 \times 10^{11}$ G and with $\tau > 10^7$ years is established. The problem is solved by assuming that the birth of pulsars can be happen at the mentioned values, too. Such births occur, probably, as a result of disruption of binary systems after the second supernova explosion in high-mass X-ray binary systems. In these binaries, mass accretion on the surface of X-ray pulsars leads to a decrease in the magnetic field from its initial value $B \approx 10^{12}$–10^{13} G to $B < 3 \times 10^{11}$ G.

Keywords: Pulsar; Evolution; Origin

1 INTRODUCTION

During the last approximately 30 years the evolution of single field pulsars has been studied on a P–$\dot{P}$ diagram. This is not surprising because the period and its deviation have been measured with great accuracy. This diagram for pulsars with distances of up to 3.2 kpc and with $\log P > -1$ and $\log\dot{P} > -16.5$ is plotted in Figure 1. These restrictions were taken into account in order to deal with a more complete single pulsar sample. As is seen from this figure, the increase in pulsar number with time deviates more and more from simple proportionality as pulsars achieve characteristic time values $\tau < 10^7$ years. This fact cannot be explained by only the assumption that pulsars with different magnetic fields may turn off at different ages. One may wonder whether this may be explained with by the luminosity decrease and/or beam narrowing of pulsars with time. Today, there is no indication that such a great change in the pulsar beam can explain the above-mentioned lack of pulsars with increasing τ, although this possibility has been carefully studied for many years (Frail and Moffett, 1993). Consideration of the luminosity will be studied in the next section.

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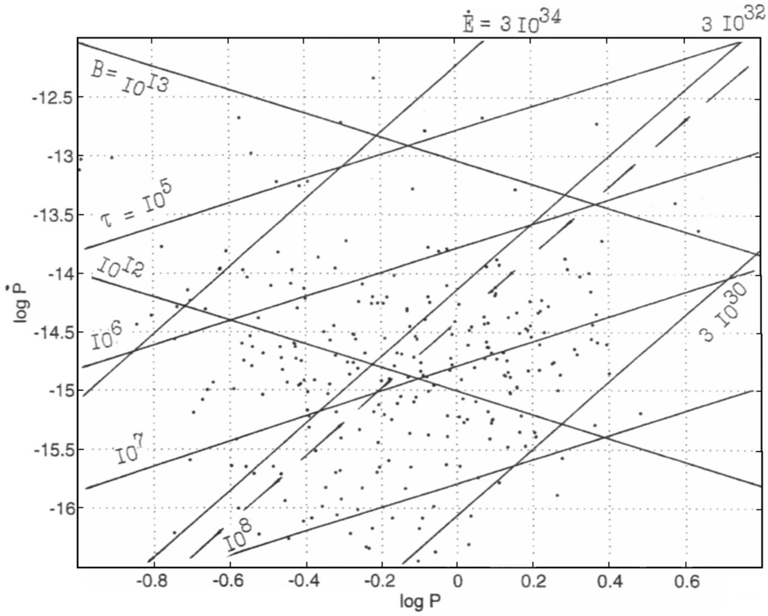

FIGURE 1 P–$\dot{P}$ diagram for single field pulsars with the distances up to 3.2 kpc and with log $P > -1$ and log $\dot{P} > -16.5$.

Figure 2 represents the $|Z|$–τ diagram for our sample of pulsars, where $|Z|$ is the absolute value of the height of pulsars from the galactic plane. As is seen, the expected increase in $|Z|$ with increasing τ is not seen for log $\tau > 7.5$ years. For smaller values of τ, $|Z|$ increases with increasing τ, but there is no linear proportionality, contrary to expectation. This cannot be the

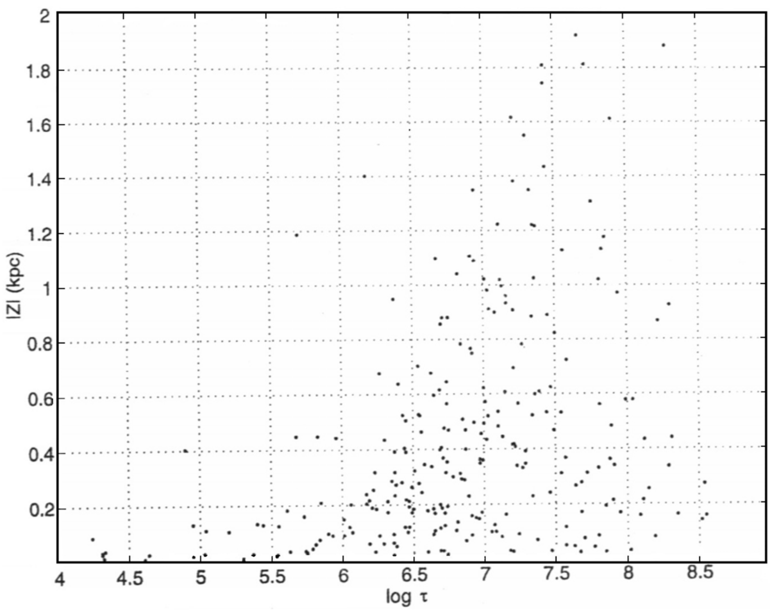

FIGURE 2 $|Z|$–τ dependence for single pulsars with $d < 3.2$ kpc.

result of the slowing of pulsars in the gravitational field of the Galaxy, because the velocities of pulsars are too high and their ages are too small to allow this to occur.

It is well known that the difference between τ and the kinematic age t of pulsars increases with increasing τ, but this fact still remains unexplained. As is seen from Figure 2, there is a large number of pulsars with small $|Z|$ at every value of τ. However, owing to the high velocities of pulsars, their number near the Galactic plane must decrease with increasing τ. We shall return to this problem in the next section.

A more important difficulty that is directly connected with the above-mentioned problems is the existence of single-field pulsars with magnetic field $B < 3 \times 10^{11}$ G and $\log \tau > 7$ years. The origin and the evolution of these pulsars cannot be explained in the framework of canonical pulsar evolution theories.

We shall discuss the possible evolution tracks of single pulsars at any age and the reasons affecting and determining these tracks.

2 SPREAD IN LUMINOSITY OF PULSARS

Pulsars are born with a large spread (three to four orders of magnitude) in luminosity (Allakhverdiev *et al.*, 1997b). In each section of the P–$\dot{P}$ diagram there are pulsars with luminosities that differ by two to three orders of magnitude (Figure 3). This is mainly because the radio luminosity $L = S_{400}d^2$ of pulsars almostly does not depend both on $\dot{P}$ and on the effective value of $B = 3.2 \times 10^{19}(P\dot{P})^{1/2}$ (here S_{400} is the flux at a frequency of 400 MHz in mJy and d is the distance of the pulsar from the Sun in kilopersecs). Here we shall use the simplest expression for the luminosity without taking into account the parameters

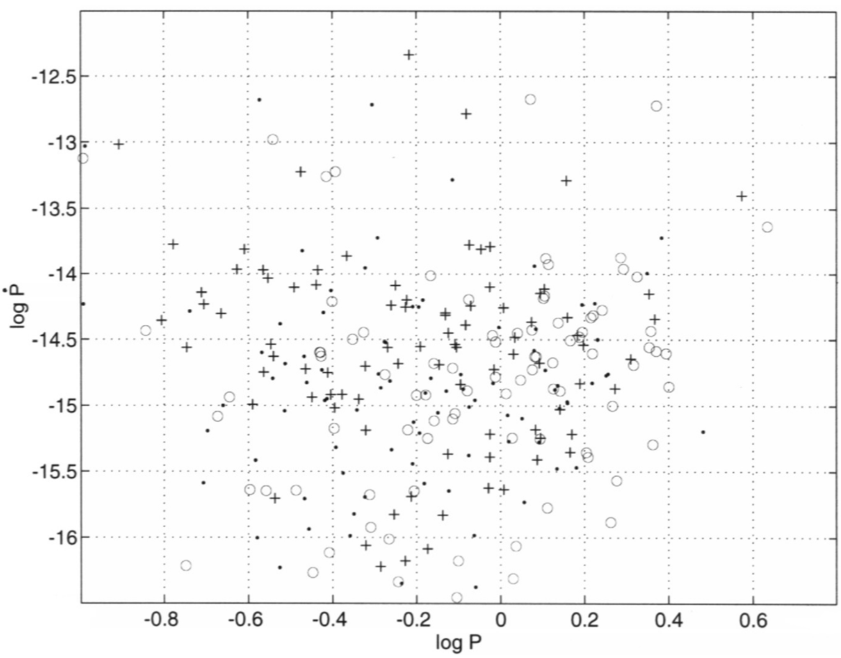

FIGURE 3 P–$\dot{P}$ diagram for pulsars with $d < 3.2$ kpc: $+$, pulsars with $\log L > 2.6$; o pulsars with $\log L < 0.6$, $\cdot$, pulsars with intermediate values of L.

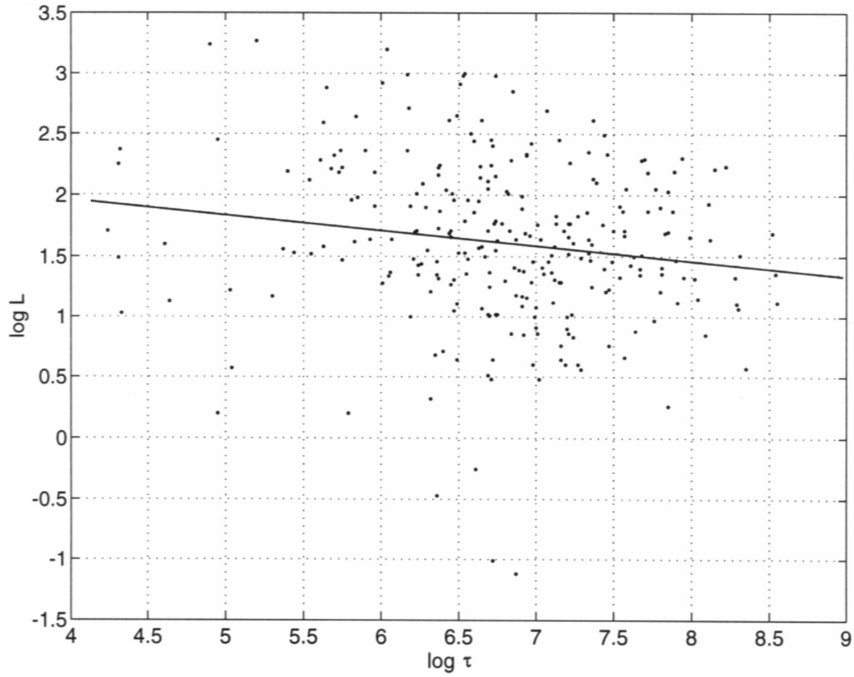

FIGURE 4 L–τ dependence for single pulsars with $d < 3.2$ kpc.

that characterize the beam and its orientation (Taylor *et al.*, 1996). In order to calculate the luminosity we have used distance values taken from the paper by Gok *et al.* (1996). The results would not change considerably if the distance values given by Taylor *et al.* (1996) had been used.

L–τ, L–P and L–$\dot{P}$ diagrams have been studied repeatedly (Gunn and Ostriker, 1970; Malofeev and Malov, 1980; Bhattacharya *et al.*, 1992). No significant dependences were found. L also almost does not depend on $\dot{E}$. (Remember that, if all rotational energy losses are due to the magnetodipole mechanism then $\dot{E} = 4(\pi^2\dot{P}/P^3)$. This is normal, if we recall that the radio luminosity of pulsars is a negligible part of the total $\dot{E}$. However, some crude dependences such as $L \propto \tau^{-0.13}$, $L \propto P^{-0.25}$ and $L \propto \dot{E}^{\,0.1}$ can be found for single pulsars.

How, on average, will L change when τ changes from 10^4 to 10^5 years if the above dependences are used? Roughly, L must change by a factor of about 3. When τ increases from 10^6 to 10^8 years, the radio luminosity of pulsars must not change by a factor of more than 2 (Figure 4). Therefore, the luminosity change of pulsars cannot influence any obtained results related to pulsar evolution.

3 FACTORS INFLUENCING THE EVOLUTIONARY TRACKS OF PULSARS

So that it is easy to see how pulsars evolve on the P–$\dot{P}$ diagram (Figure 1), some lines are plotted along which the τ, B and $\dot{E}$ values remain constant. The values of τ along these lines are equal to 10^5, 10^6, 10^7 and 10^8 years respectively. The effective values of the magnetic field B are equal to 10^{12} and 10^{13} G and the effective values of $\dot{E}$ are equal to 3×10^{30}, 3×10^{32}

and 3×10^{34} erg s^{-1}. As the lines of constant voltage are parallel to the $\dot{E}$ lines, therefore we plotted only the beginning of the turn-off zone (dashed line), according to the work of Chen and Ruderman (1993). This zone consists of all the pulsars on the right-hand side of the dashed line.

The evolution tracks of young pulsars on the P–$\dot{P}$ diagram obtained by taking into account the magnetic field decay due to high temperatures were calculated (Urpin and Muslimov, 1994). For $T > 10^6$ K, these tracks are steeper than the tracks for $B =$ constant. However, the effects of some other factors, which will be discussed below, can compensate for the influence of this decay in B. Moreover, these effects can make the tracks slope even more gently than for $B =$ constant.

As a young pulsar is located in a dense region, it can loose its rotational energy mainly because it gives energy to the surrounding medium. In this case the pulsar will evolve, as was shown by Yusifov *et al.* (1995), with a smaller braking index than the braking index for the pure magnetodipole mechanism, which is $n = 3$. As can easily be seen from Figure 1, in this case the pulsar continually increases its magnetic field up to such effective values that are needed to explain all the energy loss by only the magnetodipole mechanism. It is clear that in this case the pulsar arrives at its new position in the P–$\dot{P}$ diagram during a shorter time than τ which corresponds to the initial track with smaller B. However, the evolution time of the pulsar is longer than the τ that corresponds to the present values of P and $\dot{P}$. Therefore, a pulsar with $\tau < 10^5$ years, and as a rule having $n < 3$, must have a real age t considerable longer than τ, if $P \gg P_0$, where P_0 is the period that the pulsar had when it was born. (For the pulsar J 1811-1926–supernova remnant G 11.2-0.3 pair the value of τ is about one order of magnitude greater than the real age, because $P = 65$ ms and $P_0 = 62$ ms as reported by Torii *et al.* (1999).) Using this fact, one can easily explain the high values of implied velocities of pulsars assumed to be genetically connected with supernova remnants. As is known, the velocity is estimated by dividing the space separation of a pulsar from the assumed centre of the supernova remnant by τ. Obviously, differences between the real age t and the two mentioned values of τ will increase if the pulsar evolves with a small braking index.

With the ageing or passing of the pulsar to the tenuous medium, the reasons that lead to $n < 3$ disappear. Then, as the pulsar has a real magnetic field B less than the effective magnetic field corresponding to the end of evolution with $n < 3$, so $\dot{P}$ must be rapidly reduced. This decrease will continue until $\dot{P}$ corresponds to the magnetodipole with real B (taking into account the magnetic field decay also). Naturally, the transition of the pulsar from the track with $n < 3$ to the final track with $n = 3$ must occur through the steep path ($n > 3$). So, the pulsar will appear on the final track with $n = 3$ during significantly less time than the time if the pulsar evolves without additional energy loss (without the part of evolutionary track with $n < 3$).

The changes in direction of the evolutionary tracks and the appearance of a difference between the real age t and τ should take place also at glitches. This effect has been measured for the Vela pulsar that has strong and frequent glitches. The mean value of n for the Vela pulsar was found to be 1.4, which is much smaller than the braking indices of four pulsars measured earlier. The braking indices for the pulsars J 1513-5908, Crab, J 0540-6917, J 1119-6917, J 1119-6917 and Geminga are 2.8, 2.5, 2.0, 2.9, 3.0 and 4.3 respectively (Lyne *et al.*, 1996).

Let us consider again the analyses of the precise measurements of P and $\dot{P}$ for known pulsars. There are many such observational data for pulsars of various ages. Moreover, sometimes such measurements cover time intervals of about 20 years (Taylor *et al.*, 1993, 1996). It is worth noting that we selected only changes in P and $\dot{P}$ values that strongly exceed the observation accuracy given in these catalogues. For 40 pulsars, drastic changes in $\dot{P}$ were found. Moreover, there are both increases and decreases in the values of $\dot{P}$ for pulsars without known glitches (Taylor *et al.*, 1993, 1996). It is interesting to note that pulsars with small τ more frequently show a decrease in $\dot{P}$ (seven pulsars with log < 5.5). A noticeable decrease in P ($\Delta\dot{P}/\dot{P} \approx 10^{-4}$ during a time interval of 3 years) for these pulsars can be considered as evidence that these pulsars are in the sharp parts of their evolutionary tracks. That is why we want to attract the attention of observers to the young pulsars JJ 1932+2220, 2327 + 6151, 0742-2822, 0157 + 6212, 1825-0935 and 0543 + 2329 for which the value of breaking indices may be more than 4–5. In fact, the uncertainties in the observational data can be much greater than the given values, so that errors in the data of the pulsars may be larger. However, for the pulsars presented in this work it is highly probable that $n > 3$ will be found for some of them. In order to explain the mechanism of an X-ray pulsars some accretion and propeller models were suggested (see for example Chatterjee *et al.* (2000)). For pulsars with $\tau > 10^5$ years this mechanism may not be applicable. If some old pulsars move within dust clouds with space velocities $V < 100\,\mathrm{kms}^{-1}$, the propeller mechanism might occur, but this is not very probable. Therefore, for such pulsars we do not expect the braking index to be less than 3.

4 ON THE EVOLUTION OF PULSARS ON THE P–$\dot{P}$ DIAGRAM

As is known, almost all relatively young (with $\log \tau < 5$) pulsars are connected with concrete supernova remnants (Frail *et al.*, 1994; Allakhvrediev *et al.*, 1997a; Kaspi, 2000). Among the pulsars with relatively large values of τ, only the pulsars JJ 1852 + 0031 ($\log \tau = 5.55$), 1104-6103 ($\log \tau = 6.35$), 1627-4845 ($\log \tau = 6.42$), 1951 + 3252 ($\log \tau = 5.04$), 0659 + 1414 ($\log \tau = 5.04$) and 0502 + 4654 ($\log \tau = 6.25$) may be was born together with supernova remnants Kes 79 (G 33.6 + 0.1), G 290.1-0.8, G 335.2 + 0.1, CTB 80 (G 69.0 + 2.8), Mono-Gem (G 203.2-8.3) and G 160.9 + 2.6. At the same time, as is seen from Figure 1, pulsars with $B > 3 \times 10^{12}$ G enter into the death zone and turn off at an age of 10^7 years or less. From Figure 1, one can see that nearly half of pulsars are born with $B > 3 \times 10^{12}$ G or their effective magnetic field increases to this magnitude during a time of less than 10^5 years. Therefore, the lack (a fuction of up to 2) of pulsars with $\tau < 10^6$ years with respect to pulsars with $\tau < 10^7$ years can be easily understood.

The effective magnetic field of pulsars with $\tau < 10^5$ years may increase up to three times during their movement on the P–$\dot{P}$ diagram (owing to the observed small value of n) in comparison with initial real values. If one takes into account the decay of magnetic field by a factor of 2–3, then the maximum decrease in B in the steep part of its track may be about ten times. (That is why the pulsars born with $B > 10^{12}$ G and those which gained an effective magnetic field $B > 10^{12}$ G must set out on evolutionary tracks with $n = 3$ before their τ reaches about 10^7 years; see Figure 1).

As is seen from Figure 1, single pulsars with $B < 3 \times 10^{11}$ G can be found only for $\tau > 10^7$ years and $\dot{E} < 3 \times 10^{33}$ erg s^{-1}. Therefore, nearly all these pulsars must have tracks corresponding to $n = 3$. This is because a decay and change in the magnetic field, as shown above, occur during a time of less than 10^5–10^6 years. For pulsars with high τ values, the parts of the evolution tracks that correspond to a time interval less than 10^5–10^6 years are so short that they can be considered as a point and can be neglected.

It is seen from Figure 2 that pulsars with $\log \tau > 8$ have relatively smaller distances from the galactic plane than pulsars with $7 < \log \tau < 8$. However, pulsars with $7 < \log \tau < 8$ and with a magnetic field as weak as pulsars with $\log \tau > 8$ years are also at small heights from the galactic plane. Therefore, one has to explain not only how they were formed (as the canonical evolution that has begun in the upper left part of the diagram does not allow them to reach the position where they are!) but also why pulsars with $B < 3 \times 10^{11}$ G are nearer to the galactic plane than pulsars with the same and smaller values of τ.

In order to understand the existence of pulsars with low B and high τ near the galactic plane, it is suggested that they were born with high τ, low B and low space velocity. Naturally, these pulsars can be easily revealed, namely they are in the region where a small number of pulsars with $\log \tau > 7.5$ are placed. As mentioned, pulsars genetically connected with supernova remnants cannot reach that position as a result of evolution.

Radio pulsars in binary systems on which accretion took place in the stage of low–mass X-ray binaries have even lower magnetic fields. Was there any accretion on the pulsars considered by us? Before we attempt to answer this question, let us list the observational data.

(i) Pulsars that were born recently, that is very young pulsars, have a magnetic field $B > 10^{12}$ G. They begin their evolution in the upper left part of the P–$\dot{P}$ diagram. At the end of evolution (when the pulsar enters the death zone), these pulsars have $B > 3 \times 10^{11}$ G and $\tau < 10^7$–10^8 years.
(ii) X-ray pulsars in high-mass X-ray sources often have $B > 10^{12}$ G also. Neutron stars with small values of B often appear as bursters and rarely as pulsars in low-mass systems with disc accretion.
(iii) The magnetic field of neutron stars had decreased by up to three to four orders of magnitude at the end of intensive (disc) accretion in low-mass X-ray binaries (Bisnovatiy-Kogan and Komberg, 1974, 1976).

These observational data allow us to suggest that single pulsars with $B < 3 \times 10^{11}$ G may be born during the second supernova explosion in high-mass X-ray binaries. Such pulsars are born rarely but, as they live for a long time, the number of these pulsars is large. Note that the ‘creation’ of pulsars in binary systems in a general way was suggested earlier by bisnovatiy-Kogan and Komberg (1974, 1976).

As is known, the high space velocities of single pulsars arise becasue of an asymmetric supernova explosion rather than as a result of evolution in close binaries. The evolution in close binaries does not affect these high values. Pulsars that were born during the second supernova explosion in binary systems will have nearly the same high B and space velocities as pulsars with $\tau < 10^7$ years. At the same time, a pulsar that appeared after the first supernova explosion in high-mass X-ray binaries will have a space velocity of the order of the orbital velocity. The magnetic field of these pulsars might be considerable weaker as the result of accretion. The amount of this decrease depends on the amount of accreted matter. Therefore, the origin of pulsars with small B and $\dot{P}$ values, their location on the P–$\dot{P}$ diagram and the low average space velocities of pulsars with $\log \tau > 7.5$ becomes understandable.

5 CONCLUSIONS

Pulsars with 3×10^4 years $< \tau < 3 \times 10^5$ years may have average braking indices $n > 4$–5. The candidates for such pulsars may be JJ 1513-5908, 1932 + 2220, 2337 + 6151, 0742-2822, 0157 + 6212, 1825-0935 and 0543 + 2329.

Single pulsars with $B < 3 \times 10^{11}$ G and $\tau > 10^7$ years are simply neutron stars evolved from massive X-ray binaries. They became single radio pulsars as a result of disruption of the binary system after the second supernova explosion. A decrease in the magnetic field by two to three orders of magnitude happens because of accretion of matter from a companion pulsar.

The group of pulsars with $B < 3 \times 10^{11}$ G and $\tau > 10^7$ years has considerablely, lower space velocities than single pulsars born immediately after the first supernova explosion. The velocities of these pulsars are found by summing the orbital velocities and the centre-of-mass velocity of the binary system.

The birth of pulsars with different τ, that is in different parts of the P–$\dot{P}$ diagram, the relatively low velocities of pulsars with $B < 3 \times 10^{11}$ G, and the existence of sharp parts in evolutionary tracks of pulsars (where $n > 4$–5) can be utilized to explain the rapid increase in τ with respect to the real (kinematic) age t.

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