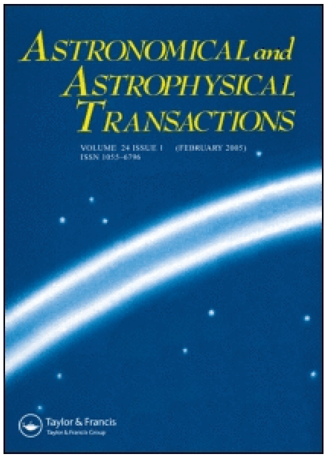

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ORIGIN OF PULSARS WITH 0.1 s < P < 0.3 s AND 5 × 10^5 YEARS < τ < 10^7 YEARS AFTER THE SECOND SUPERNOVA EXPLOSION IN HIGH-MASS X-RAY BINARIES

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The origin of same of the single pulsars with relatively low magnetic fields $B < 10^{12}$ G and with characteristic times $\tau < 10^7$ years is established. Such pulsars occur as a result of the disruption of high-mass X-ray binary systems after a second supernova explosion. In these binaries, mass accretion on to the surface of X-ray pulsars leads to the decrease in the magnetic field from its initial value $B \approx 10^{12}$–10^{13} G down to $B < 10^{12}$ G similar to the processes in low mass X-ray binaries.

Keywords: Pulsars; Evolution; Origin

1 INTRODUCTION

As is well known, the first high-mass X-ray binary (HMXB), Scorpion X-1, was discovered in 1962 (Giacconi *et al.*, 1963). A large number of HMXBs were discovered with rockets before the launch of the first X-ray satellite *Uhuru* in 1971. This is understandable as the angular resolution of the rocket observations is low, which make the uncertainties in the coordinates of the X-ray sources as high as 5° and massive stars can easily be observed for identification in the optic band. After *Uhuru* started to operate, many X-ray sources with low fluxes were also discovered. Their origin is considered to be extragalactic. The population of low-mass X-ray binaries (LMXBs), their nova type explosions and also their light curves were predicted (Amnuel *et al.*, 1973, 1974) from the data analysis of the sources which were detected by *Uhuru* (Giacconi *et al.*, 1973) and also using the poor data for Nova Cen X-2 (Harriees, 1967; Rao *et al.*, 1969) and for Cen X-4 (Evans *et al.*, 1970). Investigations of LMXBs led to very

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important results not only for X-ray astronomy but also for understanding the population of radio pulsars (PSRs) and the evolution of their magnetic fields. The long characteristic times for the magnetic field decay and the alignment of magnetic and rotation axes were understood. Bisnovatyi-Kogan and Komberg (1974, 1976) showed that accretion of matter in LMXBs must lead to the strong decay of the magnetic field of neutron stars. They also predicted the spinning of the neutron stars in LMXBs and the existence of millisecond radio PSRs with magnetic field $B < 3 \times 10^{10}$ G.

During the last approximately 40 years the evolution of single PSRs has been studied on the spin period versus time derivative of the spin period (P–$\dot{P}$) diagram. Today we may roughly explain the locations of PSRs on different parts of the P–$\dot{P}$ diagram. However, it is still difficult to understand why a large number of PSRs have periods in the interval 0.1–0.3 s and magnetic fields between 10^{11} and 10^{12} G. We assert that some of these PSRs may appear after a second supernova explosion in HMXBs. After the explosion of the massive component, an X-ray PSR must turn into a radio PSR.

2 TESTING THE ORIGIN OF THE PULSARS WITH MAGNETIC FIELDS BETWEEN 10^{11} AND 10^{12} G AND PERIODS BETWEEN 0.1 AND 0.3 s

A P–$\dot{P}$ diagram is plotted in Figure 1 for the PSRs which have period derivatives between 10^{-13} and 10^{-16} s s^{-1} and distances up to 5 kpc. These restrictions were chosen in order to deal only with a sample of single PSRs and to see clearly the regions where the examined

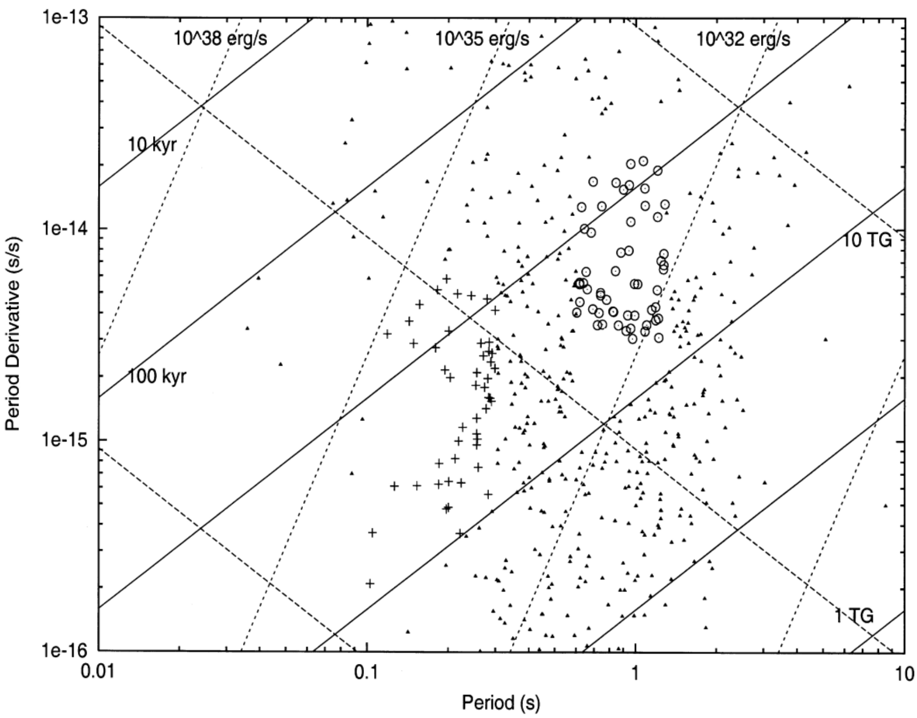


FIGURE 1 P–$\dot{P}$ diagram for all PSRs that have distances up to 5 kpc with 10^{-16} s s^{-1} $< \dot{P} < 10^{-13}$ s s^{-1}; +, PSRs that form our first sample, with 0.1 s $< P <$ 0.3 s, 5×10^5 years $< \tau < 10^7$ years; ○, PSRs that form our second sample, with 0.6 s $< P <$ 1.3 s, $\dot{P} > 3 \times 10^{-15}$ s s^{-1}, 6×10^5 years $< \tau < 10^7$ years.

PSRs are located. We had to put a limit on distance values since, the farther the PSRs the larger the errors in their distances. This was necessary if we also take into consideration that in the recent surveys many distant PSRs were discovered in the plane of the Galaxy in a narrow latitude interval (for the complete data see *ATNF Pulsar Catalogue* (2003) and Guseinov *et al*. (2002) and references therein). There is no search with similar sensitivity for most of the sky.

As seen in Figure 1, all the PSRs with ages up to 10^5 years have magnetic fields higher than 10^{12} G. From this figure we can say that PSRs are almost always born with these magnetic field values. All 23 PSRs which have genetic connections with supernova remnants (Manchester *et al*., 2001; Guseinov *et al*., 2003) are located in this part of the P–$\dot{P}$ diagram. Therefore, without any doubt, PSRs are mostly born in this region of the P–$\dot{P}$ diagram. However, this does not mean that right after a supernova explosion some PSRs cannot have magnetic field values that are several times lower at birth.

As seen in Figure 1, the number of PSRs which are located in between the constant-magnetic-field lines 10^{11}–10^{12} G and have ages up to 5×10^5 years is very small, whereas the number of PSRs having the same magnetic field values with higher ages is high. In contrast, we do not see a similar situation in the $10^{12} < B < 10^{13}$ G interval. As magnetic fields of single PSRs with ages 5×10^5–10^7 years almost do not change, their evolutionary tracks must be parallel to the constant-magnetic-field lines. Therefore, some of the PSRs with $B \approx 10^{11}$–10^{12} G may be born in the region with $P \approx 0.1$–0.3 s directly with a large value of τ. This may be due to the second supernova explosion in HMXBs. In this way, after the explosion in the massive binary, an X-ray PSR becomes a radio PSR. If we compare a PSR having such an origin with a single born PSR, the former must have a magnetic field several times smaller than that of the single born PSR even though both of them have the same initial magnetic field strengths, because magnetic field decay due to the accretion during the HMXB phase occurs. This process is similar that taking place during disc accretion in LMXBs [8, 9].

The Kinematic ages of these PSRs on average must be lower than the kinematic ages of the single born PSRs with the same values of characteristic times τ. This is reasonable since the space velocities of the single born PSRs are considerably higher than the centre-of-mass velocity of HMXBs. We should also take into account that the radio PSR which is born after the second supernova explosion continues to move with its orbital velocity, but on average the orbital velocities are also lower than the space velocities of single born PSRs. Therefore, PSRs which appear after the second supernova explosion may have, on average distances $|z|$ from the Galactic plane that are several times smaller.

In order to test this idea we have chosen two groups of PSRs with similar characteristic ages. The numbers of PSRs in each group are almost the same. In the P–$\dot{P}$ diagram, the first group has the boundaries as 0.1 s $< P < 0.3$ s, 5×10^5 years $< \tau < 10^7$ years, and the second group has the boundaries 0.6 s $< P < 1.3$ s, 6×10^5 years $< \tau < 10^7$ years and $\dot{P} > 3 \times 10^{-15}$ s s^{-1}. It is necessary to note that we specially restricted the groups that we are working on, so that the PSRs in the first and the second groups have different bands of evolutionary tracks on the P–$\dot{P}$ diagram and their number versus age distributions are similar.

For our PSR samples the $|z|$–τ diagrams are represented in Figures 2(a) and (b). As is seen, there is no considerable increase in $|z|$ with increasing τ for the first group of PSRs. At a smaller value of τ, $|z|$ increases approximately with τ, but there is no linear proportionality similar to that seen in the second group of PSRs (Figure 2(b)). As is seen in Figure 2(a), at every value of τ there is a large number of PSRs with small $|z|$ values. Because of their high velocities those single born PSRs which are near the Galactic plane must decrease as we go towards higher τ values (see Figure 2(b)). From Figure 2(a) we noticed that PSRs in the first group definitely have smaller average $|z|$ values than PSRs of the second group (see Figure 2(b)). This should be related to the appearance of newborn PSRs in the first group with different values of τ. These PSRs are directly placed in the low-B large-τ part of the P–$\dot{P}$ diagram.

For safety we checked PSRs with 10^7 years $< \tau < 10^8$ years and saw the same tendency. However, at such ages the changes in the beaming factor and the decrease in the PSR voltage

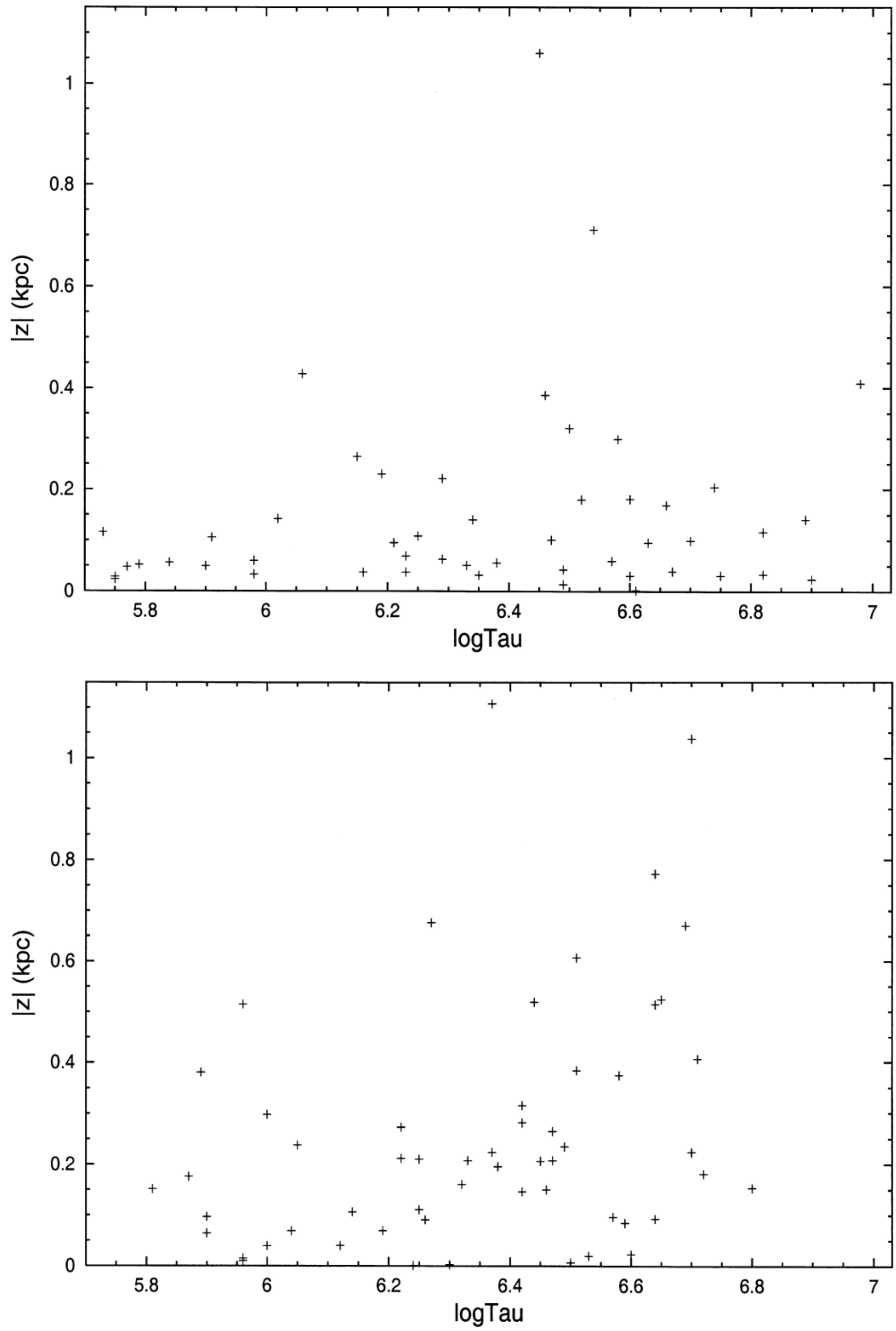


FIGURE 2 $|z|-\tau$ diagrams for the PSRs with (a) 0.1 s $< P < 0.3$ s, 5×10^5 years $< \tau < 10^7$ years and $d \leq 5$ kpc and (b) 0.6 s $< P < 1.3$ s, $\dot{P} > 3 \times 10^{-15}$ s s^{-1}, 6×10^5 years $< \tau < 10^7$ years and $d \leq 5$ kpc.

start to affect the PSR population, creating uncertainties. Naturally, this may influence the average value of the deviation from the Galactic plane.

Do the important differences that we saw in Figure 2(a) and in Figure 2(b) between the PSRs in the first group and those in the second group depend on selection effects? Can it be true that

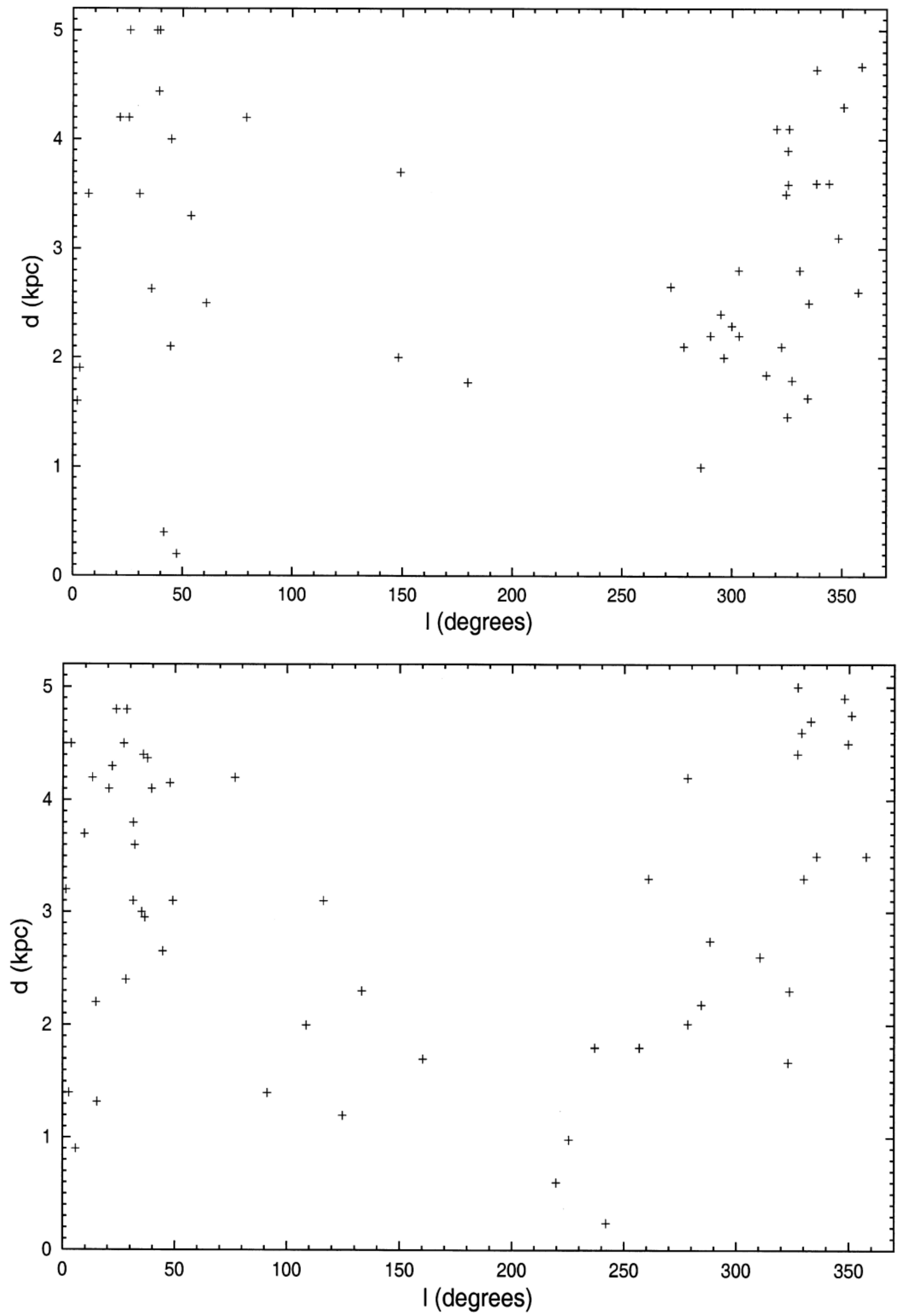
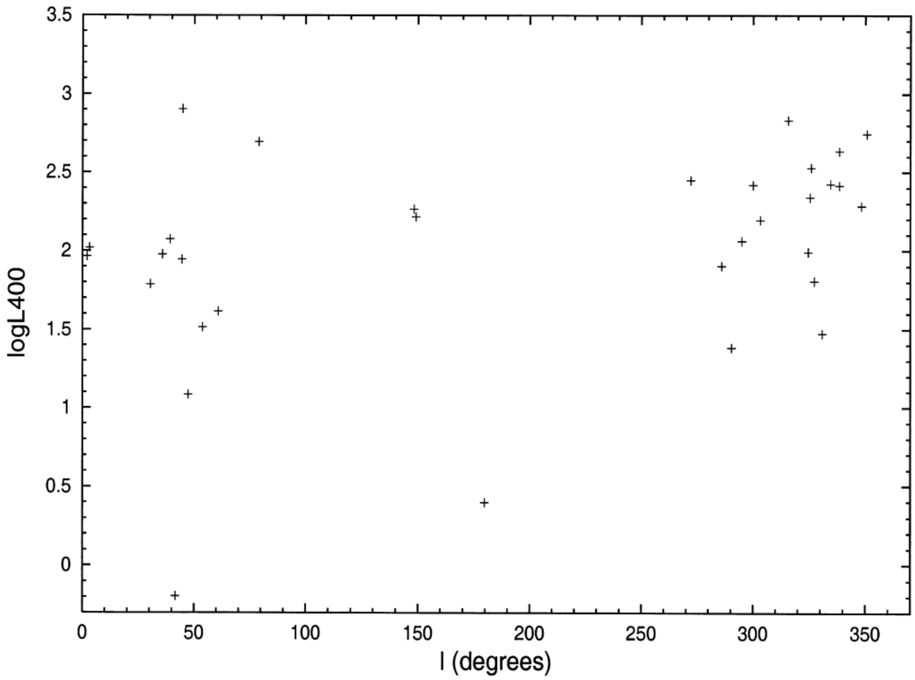


FIGURE 3 The d versus l diagrams for the PSRs with (a) $0.1\ \mathrm{s} < P < 0.3\ \mathrm{s}$, 5×10^5 years $< \tau < 10^7$ years and $d \leq 5$ kpc and (b) $0.6\ \mathrm{s} < P < 1.3\ \mathrm{s}$, $\dot{P} > 3 \times 10^{-15}\ \mathrm{s\,s^{-1}}$, 6×10^5 years $< \tau < 10^7$ years and $d \leq 5$ kpc.

different velocities and average $|z|$ values arise because other parameters of these PSRs are different? Even though this idea has a low probability of occurrence, let us investigate other parameters of PSRs in both groups in order not to leave any doubts. Can the locations of the PSRs in the first group with respect to the Sun be responsible for their small $|z|$ values when



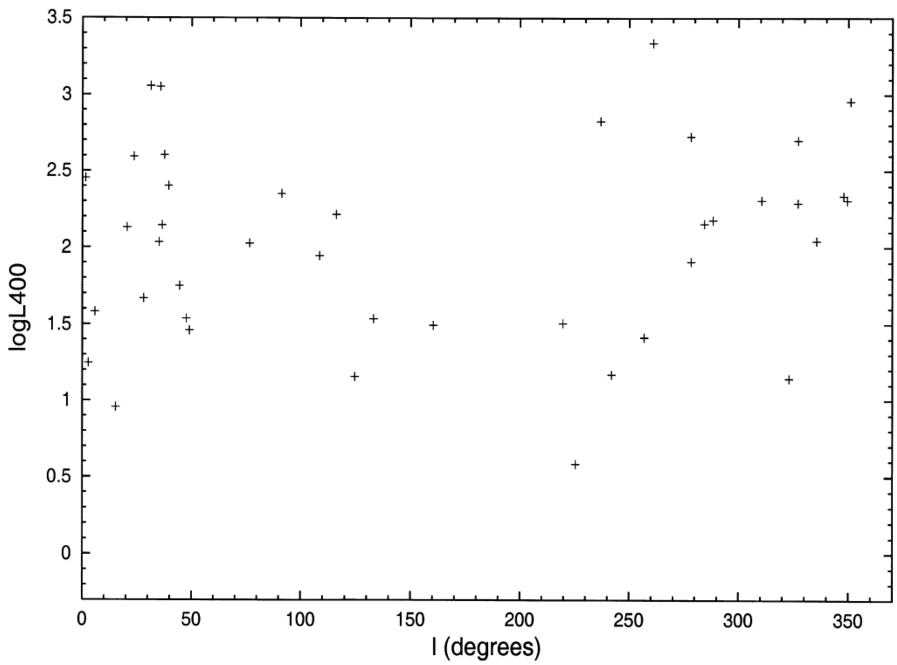


FIGURE 4 Diagrams of luminosity L_{400} at 400 MHz versus l for PSRs with (a) $0.1\ \mathrm{s} < P < 0.3\ \mathrm{s}$, 5×10^5 years $< \tau < 10^7$ years and $d \leq 5$ kpc and (b) $0.6\ \mathrm{s} < P < 1.3\ \mathrm{s}$, $\dot{P} > 3 \times 10^{-15}\ \mathrm{s\ s^{-1}}$, 6×10^5 years $< \tau < 10^7$ years and $d \leq 5$ kpc.

compared with the $|z|$ values of the PSRs in the second group? In Figures 3(a) and (b) the distance d from the Sun versus the galactic longitude l of these two samples are plotted. From these figures we deduce that PSRs in the second group are slightly farther away from the Sun than the PSRs in the first group. Thus, the distances have no effect on our results.

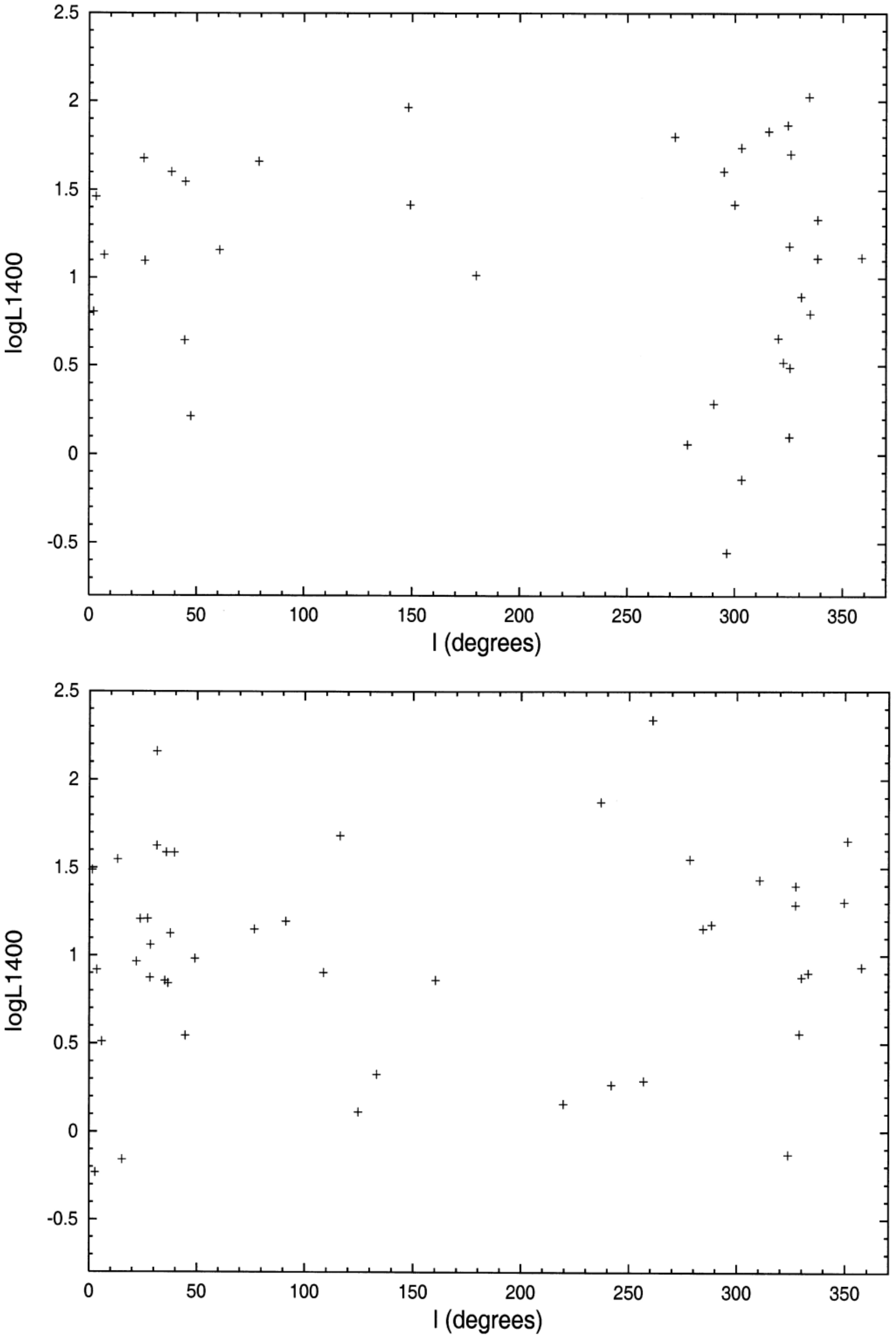


FIGURE 5 Diagrams of luminosity L_{1400} at 1400 MHz versus the galactic longitude l for PSRs with (a) $0.1\ \mathrm{s} < P < 0.3\ \mathrm{s}$, 5×10^5 years $< \tau < 10^7$ years and $d \leq 5$ kpc and (b) $0.6\ \mathrm{s} < P < 1.3\ \mathrm{s}$, $\dot{P} > 3 \times 10^{-15}\ \mathrm{s\,s^{-1}}$, 6×10^5 years $< \tau < 10^7$ years and $d \leq 5$ kpc.

In general it is known that radio luminosities of PSRs depend very weakly on their locations in the P–$\dot{P}$ diagram. In Figure 1, the locations of the PSRs in both of the groups differ slightly, but not significantly. Therefore, PSRs in both groups must have similar fluxes and luminosities. On the other hand, conditions for PSR observation depend on the directions in the Galaxy. This is expected since, in different directions of the Galaxy, PSR searches with various accuracies and sensitivities were performed at different frequencies. Luminosities at 400 MHz versus Galactic longitude are shown in Figures 4(a) and (b) whereas luminosities at 1400 MHz versus Galactic longitude are represented in Figures 5(a) and (b) for our samples. As seen from these figures, there is no difference for both groups in their directions, luminosities and fluxes. Therefore, the differences in the average values of $|z|$ for both groups of PSRs are not related to the selection effects.

3 THE DIFFERENCE IN SPACE VELOCITIES OF THE PULSARS IN THE GROUPS

Now let us discuss data about the space velocities of some PSRs from both of the groups. Some data for five PSRs from the first group and for 12 PSRs from the second group for which proper motions are known are given in Table I. As the table indicates, PSRs from the first group have not only considerably small $|z|$ values but also low space velocities. The space velocity of each PSR may roughly be estimated using the proper motion (Lyne *et al*., 1982; Bailes *et al*., 1990; Harrison *et al*., 1993; Fomalont *et al*., 1997) and distance values (Guseinov *et al*., 2002). Therefore, we saw that kinematic characteristics of these two groups of PSRs are actually different.

TABLE I Names, proper motions, d, $|z|$ and τ values of five PSRs from the first sample and of the subsequent 12 PSRs from the second sample.

PSR	μ (*mas years*$^{-1}$)	d (*k years*)	$\|z\|$ (*k years*)	*log* τ
J0358+5413	13.9[a]	2	0.028	5.75
J1453−6413	26.9[b]	1.84	0.142	6.01
J1559−4438	14.0[a]	1.63	0.181	6.60
J1932+1059	88.1[c]	0.2	0.013	6.49
J2055+3630	4.2[d]	4.2	0.409	6.98
J0502+4654	11.3[d]	1.7	0.091	6.26
J0630−2834	38.1[a]	1.8	0.519	6.44
J0653+8051	19.0[d]	2.3	1.038	6.70
J0837+0610	51.0[c]	0.6	0.266	6.47
J0946+0951	43.4[c]	0.98	0.670	6.69
J1136+1551	371.3[c]	0.24	0.224	6.70
J1509+5531	99.8[c]	1.4	1.108	6.37
J1709−1640	3.0[a]	0.9	0.212	6.21
J1913−0440	8.6[d]	3.1	0.384	6.51
J1919+0021	2.2[d]	2.95	0.316	6.42
J2225+6535	182.4[d]	2.0	0.238	6.05
J2354+6155	22.8[d]	3.1	0.010	5.96

[a]From Fomalont *et al*. (1997).
[b]From Bailes *et al*. (1990).
[c]From Lyne *et al*. (1982).
[d]From Harrison *et al*. (1993).

4 EXAMINATION OF THE X-RAY DATA OF PULSARS IN BOTH GROUPS

After the supernova explosion, as the X-ray component in HMXBs may directly show itself in the regions where τ values are high, it may have significantly large X-ray luminosity compared with other PSRs with similar characteristic times because the time that it has spent as a radio PSR is shorter than the value of its characteristic time.

Lists of PSRs from which X-ray radiation was observed in the 0.1–2.4 keV and in 2–10 keV bands were published by Becker and Trumper (1997), Becker and Aschenbach (2002) and Possenti *et al.*, (2002). As seen in these lists, from PSRs J1057−5226, J0358+5413, J0538+2817 and J1932+1059, X-ray radiation was detected. All these PSRs belong to our first group and there is no other pulsar with τ in the interval 5×10^5–10^7 years from which X-ray radiation was observed. In the above-mentioned lists there are also two PSRs, namely J0826+2637 and J0953+0755, with characteristic times several times longer. Both of these PSRs are directly located in the belt along which PSRs from the first sample evolve. Yet three PSRs, namely J1952+3252, J0117+5914 and J1302−6350, which radiate X-rays, are located on the P–$\dot{P}$ diagram right in front of the first sample of pulsars, as they have 10^5 years $< \tau < 5 \times 10^5$ years. Only Geminga PSR, which has a magnetic field of about 1.7×10^{12} G, is located in the boundary of the second sample of PSRs. All other PSRs with higher ages from which X-ray radiation have been observed are old millisecond PSRs. These deductions strongly justify what we have suggested about the origin of many of the PSRs that are born with magnetic fields between 10^{11}–10^{12} G and characteristic ages between 5×10^5 and 10^7 years.

5 CONCLUSIONS

Some of the PSRs with 10^{11} G $< B < 10^{12}$ G and with $P < 0.3$ s appear after the second supernova explosion in HMXBs. These PSRs, before the second explosion, were X-ray components of HMXBs. As a result of accretion on to these PSRs, magnetic field decay occurs. These PSRs must conserve their orbital and centre-of-mass velocities, the sum of which is on average lower than the space velocity of single born PSRs. On the other hand, distances of HMXBs from the plane of the Galaxy are not large and the real ages of the PSRs discussed may be lower than their characteristic times. Therefore, these PSRs must have low space velocities and their distances from the Galactic plane must also be smaller than those of the single born PSRs with the same values of τ. On the other hand, they must have significantly higher X-ray luminosities than the single born PSRs with similar values of τ. The observational data confirm all these expectations.

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