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About one hypothesis on the origin of Anomalous X-ray Pulsars and Soft Gamma-ray Repeaters

F.K. Kasumov, A. O. Allakhverdiev, and A.I. Asvarov[1]

Institute of Physics of the National Academy of Sciences of Azerbaijan,
33 H.Cavid Str, Baku AZ1143, Azerbaijan Republic
e-mail: astro@physic.ab.az

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Abstract. We analyze the possibility of realization of the scenario, according to which Anomalous X-ray Pulsars (AXPs) and Soft Gamma-ray repeaters (SGRs) originate from the radio pulsars with the very close initial parameters (period, magnetic field etc.) subjected to considerable and prolonged glitches. This scenario provides both an increase in the period of ordinary pulsars and the attainment of magnetic field strengths typical of these objects ($B \sim 10^{13} - 10^{14}$ G), a new class of neutron stars, called magnetars, at an insignificant initial magnetic field value $B \approx 3 \times 10^{10} - 10^{11}$ G. With this aim, the criteria to which the potential progenitors of AXPs and SGRs must be satisfied were determined and analyzed. So, taking into account the combined action of all factors (magnetic field, distance, birth place, satisfying to our criteria etc.) we restricted our analysis to 100 pulsars with $B > 5 \times 10^{12}$ G and $P > 0.5$ s. The observed characteristics of such pulsars, their association with supernova remnants, and their evolution in the $P - \dot{P}$ diagram with allowance made for the actual age of the possible AXP and SGR progenitors are shown to being in conflict with the suggested scenario and can be better described in the framework of the standard magneto-dipole model of pulsar evolution.

Key words. pulsars, AXP, SGR

1. Introduction

Recently, Lin & Zhang (2004) suggested a scenario for the origin of magnetars in which their progenitors are ordinary radio pulsars subjected to frequent (once in several years) and considerable glitches (sudden jumps in the period). In contrast to the standard models that admit a significant difference in the initial parameters of pulsars, these authors surmised that radio pulsars are born with similar parameters (spin period P, magnetic field B, etc.), but they are subjected to glitches of various magnitudes. During the lifetime of a pulsar, these glitches gradually cause an increase in P and $\dot{P}$ and, consequently, according to the formula $B \sim (P\dot{P})^{1/2}$, which is valid for the standard model of magnetodipole radiation from pulsars, a growth of the magnetic field of pulsars.

This scenario provides both an increase in the period P of ordinary pulsars and the attainment of magnetic field strengths typical of anomalous X-ray pulsars (AXPs) and soft gamma repeaters (SGRs) ($B \sim 10^{13} - 10^{14}$ G), a new class of neutron stars called magnetars, at an insignificant initial magnetic field strength, $B \approx 3 \times 10^{10} - 10^{11}$ G. Lin and Zhang (2004) estimated the characteristic time (at reasonable initial parameters of pulsars) it takes to reach the AXPand SGR parameters to be $\geq 2 \times 10^5$ yr, with the characteristic time it takes for pulsars to reach the region where AXPs and SGRs are located in the $B - P$ diagram being $\sim 1.5 \times 10^4$ yr. Thus, for this scenario to be realized, the following requirements must be met.

(1) The existence of permanently operating mechanisms in a group of radio pulsars with uniform or similar initial parameters (P, B, M, ets.) that lead to jumps in the period, i.e., glitches, with significant magnitudes and rates: $\Delta\dot{P}/\dot{P} \geq 0.0028$ and $\tau \sim 0.3$ yr^{-1}.

(2) No genetic association of magnetars and their possible progenitors with supernova remnants (SNRs), especially with those younger than 10^5 yr, must be observed, since the characteristic time it takes for a pulsar with reasonable initial parameters and with the above magnitudes and rates of glitches to reach the ASPand SGR parameters is $t \geq 2 \times 10^5$ yr.

(3) The radio pulsars that are the possible progenitors of magnetars (AXPs and SGRs) must show a tendency for the magnetic field to grow with increasing period; i.e., these must be mostly pulsars with long periods ($P > 0.5$ s) and with already grown magnetic fields ($B > 5 \times 10^{12}$ G, see below).

Send offprint requests to: F.K. Kasumov

(4) In the $P - \dot{P}$ diagram, the group of such pulsars must evolve toward the upper right corner; i.e., P and B must exhibit a positive correlation with one another and with the pulsar age.

Below, we analyze the answers to the above questions and show that there are no serious grounds for the realization of this scenario for the evolution of radio pulsars into AXPs and SGRs.

2. The magnitude and rate of glitches for possible AXP and SGR progenitors

Lin and Zhang (2004) used PSR J1757.24 with $P = 0.25$ s, $\dot{P} = 1.28 \times 10^{-13}$, and $B_0 = 2.6 \times 10^{11}$ G as an example to construct their scenario. In the opinion of the authors, the possible genetic association of this pulsar with the SNR G5.4-1.2 with an age of $\sim 10^5$ yr and the extremely small proper motion of the pulsar are indicative of a growth of the magnetic field over its lifetime. A giant glitch, $\Delta\dot{P}/\dot{P} \geq 0.0037$, was actually observed in this pulsar (Lyne et al. 1996). However, it should be noted that no discrepancy between the ages of the pulsar and the SNR arises in several papers because of the more accurate estimate of the SNR age with allowance made for the peculiarity of the medium in which it is expanding (Gvaramadze 2004) as a result of invoking the fall-back accretion model in estimating the pulsar age (Marsden et al. 2002).

Glitches of various magnitudes are known to be observed in many, mostly young radio pulsars, as, e.g., the Vela and Crab pulsars (the ATNF Catalog, Manchester et al. 2004). By now, more than several hundred glitches have been observed in about 100 pulsars; in 18 of them, they are significant, $\Delta P/P \leq 10^{-6}$, $\Delta\dot{P}/\dot{P} \leq 10^{-5} - 10^{-2}$ (Lyne et al. 2000). In our sample of potential progenitors, which includes ~ 100 objects, glitches were observed only in four pulsars: PSR J1740-301 ($\Delta\dot{P}/\dot{P} = 0.0002 - 0.003$), PSR J0528+2200 (0.00046),PSR J1341-6220 ($0.00015 - 0.003$), and PSR J1801-2304 (0.00001). As we see, the glitches are comparable inmagnitude to the glitch of the basic object PSR J1757-24 in the model of Lin and Zhang (2004), with the rate of glitches in these pulsars varying within the range $1 - 0.2$ per year. Thus, the parameters of glitches in the possible AXPand SGR progenitors included in our list correspond to those adopted in the model of Lin and Zhang (2004). Note that glitches were also observed in magnetars (Osso et al. 2003; Kaspi et al. 2003).

3. The association of possible AXP and SGR progenitors with supernova remnants.

The currently known association of AXP 1E2259+586, AX J1846-0258, and 1E1841-045 with the SNRs G109.1-1.0, G29.6-0.1, and G274+0.0, respectively, is beyond question for most researchers (see Gaensler 2004). According to Tagieva and Ankay (2003), the number of such possible associated pairs can reach six, with the ages of the SNRs in these pairs, except one (AXP 1E 2259+58, $t \sim 2 \times 10^5$ yr), being $\sim 10^3 - 10^4$ yr.

In addition, there are also seven objects that are generically associated with SNRs in the list of radio pulsarspossible AXP and SGR progenitors (these must be pulsars with $P > 0.5$ s and $B > 5 \times 10^{12}$ G). These pairs are: PSR J1734-33 and G354.8-0.8, PSR J1119-61 and G229.2-0.5, PSR J1726-35 and G352.2-0.1, PSR J1632-48 and G336.1-0.2, PSR J1524-57 and G322.5-0.1, PSR J1124-59 and G229.0-1.8, PSR J1413-61 and G312.4-0.4 (Manchester et al. 2002). The ages of all these SNRs do not exceed 105 yr. Note that there is no significant discrepancy in the estimated characteristic ages of these pulsars and the SNR ages, which basically provides evidence for the suggested scenario (similar to the basic pair PSR J1757-24 and G5.4-1.2).

Note also that the recent discovery of the possible magnetar CXO J161710.2-455216 (Muno et al. 2005) in the young cluster Westerlund 1, whose progenitor is a fairly massive ($M > 40M_\odot$) star, also suggests that the maximum ages of magnetars are no older than 4×10^6 yr.

4. The sample of radio pulsars - potential AXP and SGR progenitors, the $B - P$ diagram.

As we noted above, the small number of AXPs and SGRs (~ 10 objects; they are denoted by the ("+") sign in Figs. 1 and 2) suggests that, even at the same birthrate of radio pulsars and AXPs and SGRs (which is basically a limiting assumption for AXP and SGR), the number of the latter is approximately a factor of 1.5 smaller. Indeed, the ratio of the number of radio pulsars $N_{PSR} = R_{PSR} \cdot t_{PSR}$ to the number of magnetars $N_M = R_M \cdot t_m$ at $R_{PSR} = R_M$ is proportional to $\sim t_{PSR}/t_M$, where R and t are the birthrate and maximum ages of these objects, respectively. Since $t_{PSR}/t_M \approx 10^7/10^5 = 100$ and the observed ratio is $\sim 1400/10 = 140$, the number of AXPs and SGRs is a factor of 1.5 smaller than the number of radio pulsars. According to Lin and Zhang (2004), of all the radio pulsars, only those that are subjected or can be subjected to glitches can turn into magnetars, because an increase in the magnetic field strength is required (this is a mandatory condition; otherwise their mechanism is inoperative). The fraction of such pulsars at best does not exceed $\sim 1/10$ of all radio pulsars. Thus, if the numbers of AXPs and SGRs and radio pulsars with allowance made for their lifetime are assumed to be equal, then the number of possible progenitors of magnetars among all of the radio pulsars will be approximately a factor of 15 smaller, i.e., no more than 100 objects

The next factor that limits the number of possible progenitors of magnetars is the magnetic field strength B. For the canonical parameters of neutron stars and the observed values of P and $\dot{P}$, the magnetic field strength $B = 3.2 \times 10^{19} (P\dot{P})^{1/2} \sim 10^{11} - 10^{13}$ lies within the range $10^{11} - 10^{13}$ G. Taking into account also the magnetic field decay on a time scale $\tau_{\rm m} \sim 3 \times 10^6$ yr (Guseinov et al. 2004), we find that the initial values can be a factor of

~ 3 higher. Therefore, among all of the radio pulsars subjected to prolonged glitches, those of them whose magnetic field has increased to $\sim (3-8)\times 10^{12}$ G have a chance to turn into magnetars.

Finally, according to the estimates of Lin and Zhang (2004), it takes $\sim 2\times 10^5$ yr for a pulsar to reach the AXP and SGR state at the chosen glitch parameters; the time it takes to reach the AXP and SGR region is $\sim 1.5\times 10^4$ yr, i.e., the objects subjected to magnetic field preamplification spend approximately 1/10 of the time in the pre-magnetarstage. At $P_0 \sim 10$ ms, the periods of pulsars can increase to ~ 0.5 s in this time.

Taking into account the combined effect of all these factors, we will restrict our analysis to pulsars with $B \geq 5\times 10^{12}$ G and $P \geq 0.5$ sec. According to the catalog of Manchester et al. (2004), their number is ~ 90.

In Fig. 1, B is plotted against period P for our sample of objects. At a mean velocity of $\sim$ 300 km s^{-1} (Allakhverdiev et al. 1997), pulsars younger than 3×10^5 yr can recede in $|Z|$ from their birthplaces (where $|Z|$ is the absolute value of the pulsar distance from the Galactic plane) to no more than 100 pc, and, during $\sim 10^6$ yr, to $|Z| \geq 300$ pc.

Our assumed mean velocity has been confirmed in a number of recent papers. Thus, for example, a recent study of the proper motions of pulsars by Hobbs et al. (2005), which covered 233 objects, showed that the pulsar velocity distribution is Maxwellian, with an rms z velocity component of 265 km s^{-1}, and only three objects have velocities higher than 1000 km s^{-}1. Including other velocity components and other distance models results in such a scatter of velocities that $\sim 70\%$ of the pulsars will have velocities in the range $200-400$ km s^{-1}. Therefore, we may take the value that we used, ~ 300 km s^{-1}, for the mean z velocity component. Incidentally, we know only one pulsar with a velocity V > 1000 km s^{-1} measured independently of the assumed distance (Chatterjee et al. 2005). Note also that the results of these works do not confirm the bimodality in the pulsar velocity distributions (see Arzoumanian et al. 2002).

We restricted our sample to relatively young pulsars with $|Z| < 100$ pc (crosses in Fig. 1) and to old pulsars with $|Z| > 300$ pc (open circles). In estimating the values of $|Z|$, we used data from the catalog of Guseinov et al. (2002), in which the distances to pulsars, in our opinion, are most accurate. Note also that, according to the most recent ATNF Catalog (Manchester et al. 2004), the distances to the pulsars of our sample are very close to those we adopted. We excluded pulsars with 100 pc $< |Z| < 300$ pc from our analysis for the age difference to be distinct. To eliminate the possible selection of distant objects and the inaccurate distance determination and to take into account the deviation of the pulsar birthplaces from the geometric plane of the Galaxy (for more detail, see Allakhverdiev et al. 2005), the pulsars with $d < 5$ kpc for which $|Z| < 100$ pc are enclosed in squares in Fig. 1, while the pulsars with $|Z| > 300$ pc are denoted by filled circles.

5. The $P-\dot{P}$ diagram and the possible pattern of evolution of AXP and SGR progenitors

Based on our sample (see the previous section), we plotted the $P-\dot{P}$ diagram in Fig. 2 for radio pulsars, possible AXP and SGR progenitors. The notation in this figure is the same as that in Fig. 1. Let us assume that these pulsars or some of them have indeed undergone magnetic field preamplification under the action of glitches and reached the observed values of B and P in 10^4 yr. In the ensuing 10^5-10^6 yr, they must reach the AXP and SGR region in the $P-\dot{P}$ diagram. In this case, the distribution in the diagram must show a tendency for their real age to increase. The real age of pulsars is their kinematic age, which must exhibit a linear increase with distance from the Galactic plane with allowance made for the birthplace of pulsars in various parts of the Galaxy and their deviation from the geometric plane of the Galaxy (see Hansen and Pinney 1997; Berdnikov 1987).

As we see from Fig. 2, there is no tendency for the density of old objects to increase with P both with and without the selection. The reverse is true: young pulsars with $|Z| < 100$ pc are almost uniformly distributed up to a period $P > 5$ s. Moreover, as we see from Figs. 1 and 2, no increase in the magnetic field with period and true age of pulsars is observed. Indeed, among old pulsars with $|Z| > 300$ pc, only three of the 13 objects without any distance limitation and one of the five objects at $d < 5$ kpc have magnetic fields stronger than 10^{13} G. At the same time, among young objects ($|Z| < 100$ pc) with $P > 2$ s, 11 of the 15 without any distance limitation and four of the five at $d < 5$ kpc have $B > 10^{13}$ G.

Of course, it should be kept in mind that most of the highly magnetized radio pulsars were discovered in the most recent low-latitude survey in Parkes, and this can lead to a certain selection of high-latitude pulsars. Nevertheless, the currently available data do not confirm the pattern of evolution within the framework of the suggested scenario for the origin of AXPs and SGRs.

The solid curves in Fig. 2 describe the evolution of pulsars in the combined "dipole + propeller" model suggested by Menou et al. (2001) and Alpar et al. (2001) at various initial magnetic fields B and accretion rates. As we see, this model, just as for all pulsars (Allakhverdiev et al. 2005), does not describe the evolution of these highly magnetized objects along the propeller-dominated branch either. Indeed, the objects with $|Z| > 300$ pc (open circles in Figs. 1 and 2) concentrate in the lower right part of the diagram, while the objects with $|Z| < 100$ pc fall better on the tracks of the combined model, which is in conflict with the basic idea of the model. Only the purely dipole model (dashed lines) is consistent with the observational data on the age characteristics of the objects.

6. Conclusions

Thus, our analysis showed that none of the above main conditions for the realization of of the suggested scenario

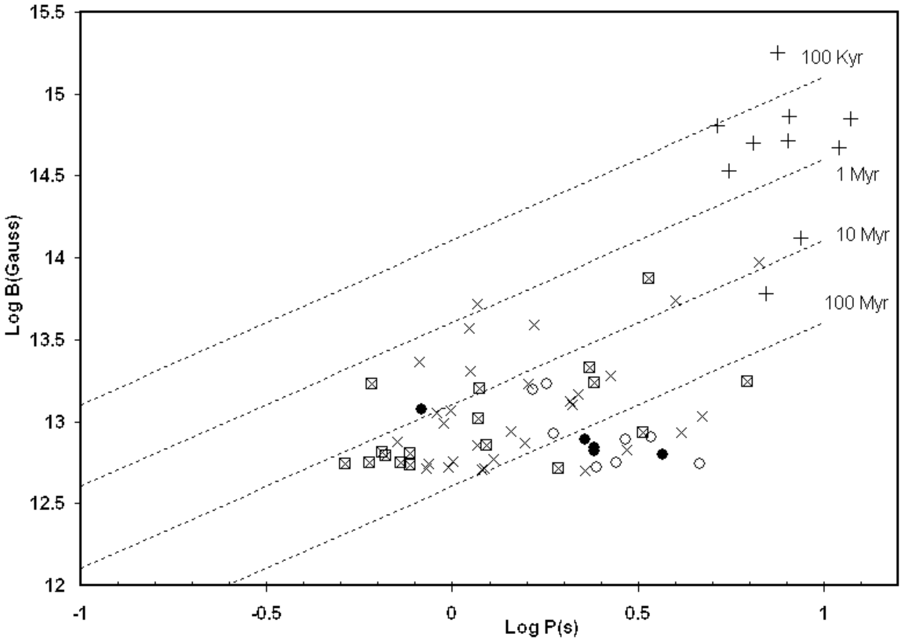

Fig. 1. Magnetic field B vs. spin period P for pulsars with $B > 5 \times 10^{12}$ G and $P > 0.5$ s. The straight lines correspond to a constant characteristic age τ.

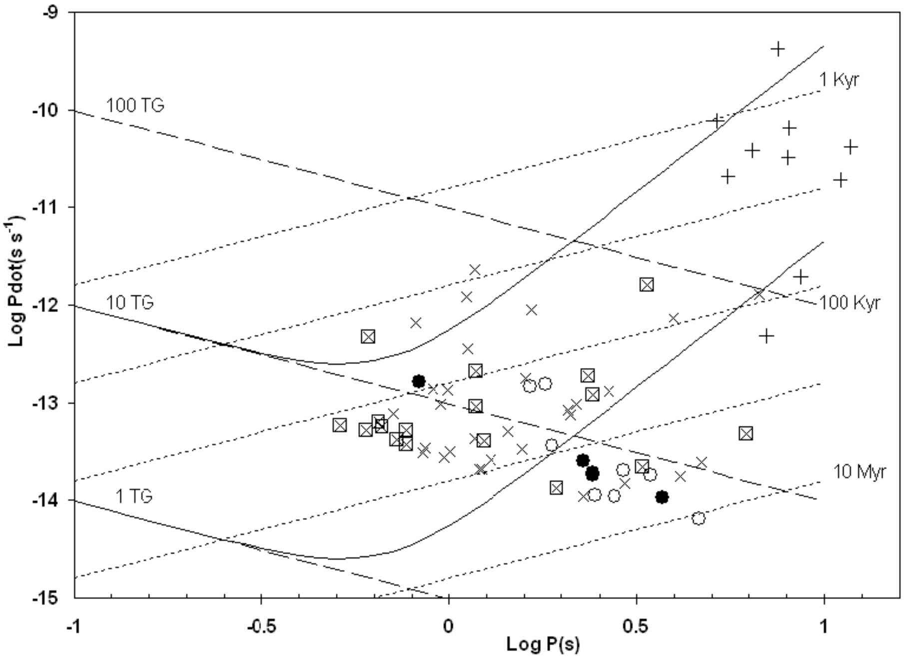

Fig. 2. $P - \dot{P}$ diagram for pulsars with $B > 5 \times 10^{12}$ G and $P > 0.5$ sec. The dotted lines are the lines of constant characteristic age τ ; the dashed lines are the lines of constant magnetic field B. The solid lines are the evolutionary tracks described by the combined model.

(with the possible exception of the first one) is confirmed by observational data. Observational data provide evidence for the universally accepted views of the evolution of pulsars in the $P - \dot{P}$ diagram (Ruderman 2001).

The special, different from the standard scenario, evolutionary path of AXPs and SGRs still retains its status (Thompson and Duncan 1995; Malov et al. 2003). Therefore, it should be noted that the alternative propeller or fall-back model (Chatterjee et al. 2000; Alpar et al. 2001) also explains the discrepancy between the characteristic and real (kinematic) ages of pulsars (Marsden et al. 2001; Shi and Xiu 2003). However, this model proposed to explain the evolutionary tracks of all pulsars by the combined action of the magnetodipole and propeller mechanisms runs into serious difficulties (Tagieva et al. 2003; Allakhverdiev et al. 2005). In the light of the discovery of X-ray radiation from one highly magnetized pulsar, PSR J1718-37 ($B \sim 7.4 \times 10^{13}$ G, Kaspi and McLaughlin 2004), as well as the analysis of the influence of neutron-star parameters and their possible variations with time on the evolutionary tracks of pulsars in the $P - \dot{P}$ diagram, other hidden parameters of neutron stars (e.g., the mass, see Kaspi and McLaughlin 2004; Guseinov et al. 2005) should probably be taken into account in standard evolutionary scenarios.

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