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Some Constraints on the Evolutionary History of the Binary Pulsar PSR 1913+16

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Summary. It is argued that the combination of short pulse period (0.059 s) and weak surface dipole magnetic field strength ($B_0 \sim 3\ 10^{10}$ G) of PSR 1913+16 is excluded for a newly born pulsar (i.e. with age $<10^7$ yr). This yields support to the suggestion made by Smarr and Blandford that PSR 1913+16 obtained its short pulse period during a spiral-in history, in which it underwent heavy accretion of matter with angular momentum from its companion. The shortest possible pulse period compatible with its magnetic field in such a case is ~ 0.04 s. As this spiral-in will have completely circularized the orbit, its presently large orbital eccentricity indicates that a second supernova explosion must have taken place in the system and, consequently, that its companion is also a neutron star (or a black hole). It is argued that the progenitor system was a binary with component masses $\geqq 8\ M_\odot$. The various possible types of radio pulsars resulting from the evolution of close binaries are discussed.

Key words: pulsars – binaries – neutron stars

1. Introduction

The binary pulsar PSR 1913+16 differs from most radio pulsars in a number of respects (Smarr and Blandford, 1976; Taylor et al., 1977). Its rotation period of 0.059 s makes it the second fastest known pulsar. Its period derivative is, however, extremely small, i.e. $\dot{P}=8.8\ 10^{-18}$ s s^{-1}. For comparison, the period derivative of the Crab pulsar PSR 0531+21 is $4.2\ 10^{-13}$ s s^{-1}. The exceptionality of its combination of P and $\dot{P}$ is best demonstrated in the $\dot{P}$ vs P diagram of radio pulsars (Fig. 1). The observed slowdown rate of this pulsar is consistent with a very small value of the surface dipole field strength B_0 of the order of $3\ 10^{10}$ G, whereas the bulk of the radio pulsars have fields of 10^{12}–10^{13} G (Smith, 1977; Taylor et al., 1977). It seems a reasonable hypothesis that its abnormal (P, $\dot{P}$) combination is connected with a special evolutionary history – involving a rather complicated history of several phases of mass transfer in a close binary (Flannery and van den Heuvel, 1975; Smarr and Blandford, 1976). Its short binary period $\sim 7^h45^m$ suggests a spiral-in history, through a phase of large loss of mass and orbital angular momentum. Such scenarios have been proposed for example by Flannery and van den Heuvel (1975), by Taam et al. (1978), Taam (1979), Delgado (1979), and Tutukov and Yungelson (1979).

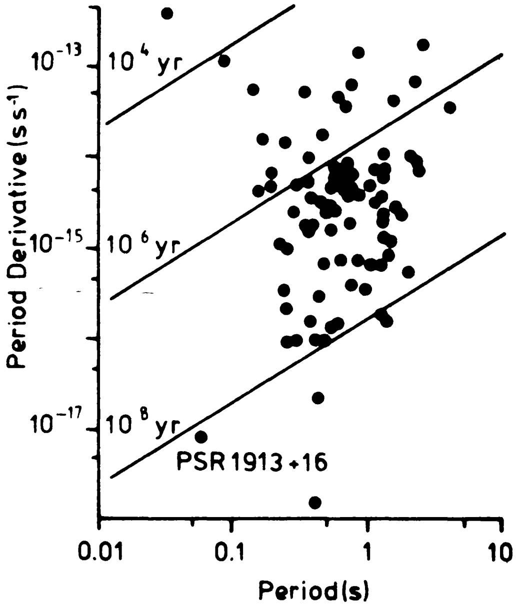

Fig. 1. The position of PSR 1913+16 in the $\dot{P}$ vs. P diagram for 87 radiopulsars (after Manchester and Taylor, 1977). Lines of constant spin-down age $P/2\ \dot{P}$ are indicated

The aim of this paper is to examine in the framework of a spiral-in scenario the possible ways in which the binary pulsar could have obtained its present characteristics – notably its low surface field strength – and to discuss possible implications of this history for the origin of radio pulsars in general. In Sect. 2 we briefly review suggested evolutionary scenarios leading to the formation of a binary radio pulsar. In Sect. 3 we consider the possible ways of decay of the dipolar field of a neutron star. Section 4 deals with the rotational history of the first born pulsar in a close binary and in Sect. 5 some additional constraints on the evolutionary history are considered.

2. Possible Evolutionary Scenarios

A) Origin from a Massive Binary

We consider the evolution of an early-type binary with components of masses 20 $M_\odot$ and 8 $M_\odot$, respectively (cf. de Loore et al., 1975). The "standard" evolutionary scenario for a massive X-ray

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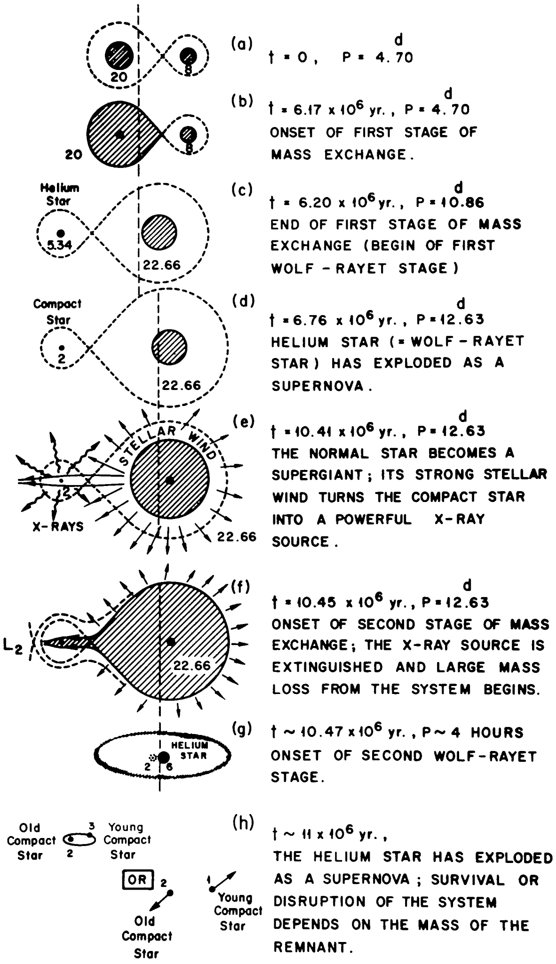

Fig. 2. Evolutionary scenario of a massive X-ray binary. The formation of a binary pulsar or two runaway pulsars (cf. De Loore et al., 1975; van den Heuvel, 1974, 1977)

binary such as 3 U 0900−40 consists of the following stages, depicted in Fig. 2 (cf. van den Heuvel, 1977). (We ignore here the effects of mass and angular momentum loss from the system during phases of mass transfer as these effects are not expected to affect the general outline of the evolutionary picture, which is the only thing that interests us here).

a–b) The primary star, being the more massive component, evolves most rapidly and about 6 10^6 yr after the birth of the system overflows its Roche lobe and transfers its hydrogen-rich envelope to its companion.

c) The system now consists of a helium star of 5.34 $M_\odot$ and a main-sequence star of 22.6 $M_\odot$.

d) Within 6 10^5 yr after the mass exchange, the helium star terminates helium and carbon burning and its degenerate core implodes to form a neutron star or a black hole. The resulting supernova explosion (SNE) is not expected to disrupt the binary.

d–e) At the moment of the explosion the 22.6 $M_\odot$ star will still be in an early stage of hydrogen burning and it will take another 4 10^6 yr before it leaves the main sequence and in its turn begins to overflow the Roche lobe. During this long "quiet phase" the newly born neutron star will not – except for the first few 10^4 yr – be seen either as a radio pulsar or an accreting X-ray binary. We shall discuss this phase in greater detail in the next section.

e) During the brief interval of time ($\sim 10^4$–10^5 yr) when the massive star is an early supergiant (with a radius close to that of its Roche lobe), the neutron star will be an X-ray source (f), powered by accretion from a wind or from beginning Roche-lobe overflow. Soon after the onset of the Roche-lobe overflow the envelope of the supergiant becomes thermally unstable, resulting in mass transfer on a thermal timescale at a rate of some $\gtrsim 10^{-4}$ $M_\odot$/yr. This will extinguish the X-ray source. Since the relativistic star cannot accept all the mass transferred to it, one expects much of it to be expelled from the system. The system will shrink rapidly due to the large specific angular momentum of the lost matter (van den Heuvel and De Loore, 1973). The spiralling-in of the neutron star is expected to terminate when only the helium core of the companion is left (van den Heuvel and De Loore, 1973; Tutukov and Yungelson, 1979. See Taam et al., 1978 for an alternative picture).

h) Some 5 10^5 yr later the helium star will explode. As the helium star is the more massive component of the system, it is quite well possible that in the explosion more than half the mass of the system will be ejected, causing it to be disrupted. In case that the system is not disrupted, it may resemble the binary pulsar PSR 1913+16 – two relativistic stars moving around the common centre of gravity in a very eccentric orbit. In fact, the very high eccentricity of this system ($e = 0.615$) indicates that it was almost disrupted in the last SN explosion.

B) Origin from an Intermediate Mass Binary

As argued by Webbink (1975) and by Smarr and Blandford (1976) the only viable alternative scenario is one in which the progenitor system was a rather wide intermediate mass binary with components of, say, 7 $M_\odot$ and 6 $M_\odot$, and the present companion is a white dwarf. In such a system, the first stage of mass transfer is expected to lead to the formation of a wide binary consisting of a ~ 1.3 $M_\odot$ Carbon-Oxygen white dwarf and an 11.6 $M_\odot$ companion. When the 11.6$M_\odot$ companion becomes a red supergiant with a ~ 3 $M_\odot$ helium core, the white dwarf spirals-in and removes the hydrogen-rich envelope of the supergiant. When the remaining 3 $M_\odot$ helium star explodes it leaves a young neutron star and a white dwarf in an eccentric orbit.

3. Young or Old Neutron Star?

We first consider scenario A.

Since PSR 1913+16 is spinning fast, it is tempting to assume that it is associated with the most recent supernova in the system. From the fact that no radio remnant of the explosion has been detected, one may conclude that this SNE occurred more than a million years ago. On the other hand, the low z ($\lesssim 200$ pc) of PSR 1913+16 in combination with the expected runaway velocity of the system of $\gtrsim 100$ km s^{-1} imparted by the last SNE (Flannery and van den Heuvel, 1975) make an age much larger than 10^6 yr (since the last SNE) rather unlikely (cf. Smarr and Blandford). If the pulsar were indeed born in the second SNE, then it must have been born with a period of about 0.05 s *and* with the presently observed *low* magnetic fieldstrength (~ 3 10^{10} G), since the decay times of pulsar magnetic fields are $\sim (0.5$–$1) \times 10^7$ yr (see below). However, it is very unlikely that a newly born neutron star with a period as small as 0.05 s can have such a small value for dipolar field, for the following reasons.

From the analysis by Flowers and Ruderman (1977) one expects the exterior magnetic field of a neutron star to be a fossil field, which is anchored into the solid crust from the moment at which the crust solidified. This is expected to have happened at a time $T_{xtl} \simeq 5\ 10^3$ s (for crustal density of $3\ 10^{13}$ g/cm^3) after the birth of a neutron star. This exterior dipolar field is from then on maintained by toroidal electric currents in the crust and its decay time will be the ohmic dissipation time of the currents which is expected to be of the order of $T_D \simeq 10^7$ yr. Indeed the observations indicate that radio pulsars do turn off with ybout a timescale of (0.5–1) 10^7 yr (Smith, 1977). At the onset of the first $5\ 10^3$ s, when the entire neutron star was still fluid, the field is expected to have had a very great strength, due to dynamo action during the collapse phase of the stellar core, when the rotation rate was enormously accelerated. I.e. the initial field strength is expected always to have been near the upper limit possible, which is 10^{13}–10^{14} Gauss. However, an axisymmetric polar magnetic field in a uniformly conducting fluid is known to be unstable to motions that diminish the exterior dipole field. The characteristic timescale for the magnetic field to readjust itself through internal fluid motions, is the magneto-hydrodynamic timescale (Flowers and Ruderman, 1977)

$$T_{\mathrm{MHD}} \simeq (2\Omega/k^2 v_A^2) \sim 10^6 (\lambda_6 \varrho_{15}/B_{12}^2)\Omega_3 \text{ s} \tag{1}$$

in which λ_6 is the characteristic wavelength of the fluid motions in 10^6 cm, ϱ_{15} is the average density in 10^{15} g/cm^3, B_{12} is the field-strength in 10^{12} G; Ω_3 is the angular velocity or rotation in 10^3 s^{-1}; λ_6 will be of order 1 (the neutron star radius).

For an initial pulse period of 0.05 s, and $B_{12} \leqq 1$, one has $T_{\mathrm{MHD}} \geqq 1.5$ d $\gg T_{xtl}$, so when B_{12} has dropped below unity, the initial field has no time to further rearrange itself into a weaker configuration before the crust freezes. With $B_{12}=1$, only in pulsars with $P \geqq 1$ s the field can still undergo some decay before the crust freezes. Hence, a young pulsar can either have a short pulse period together with a strong field or a long pulse period together with a weaker field, while other combinations are excluded. According to this analysis the combination $P=0\overset{s}{.}059$, $B_0=3\ 10^{10}$ G as observed in the binary pulsar is never expected to occur for a young neutron star. This, therefore, seems to rule out scenario B. On the other hand, if in scenario *A* this pulsar was the first born neutron star in the system, then enough time may have elapsed for the surface field to decay significantly.

We saw in Sect. 2, that the time between the first and second SNE in a massive binary system is expected to be $\geqq 5\ 10^6$ yr. If PSR 1913+16 originated from a wide binary system of intermediate mass, i.e. with components of $\sim$7–8 $M_\odot$, still two SNE in the system are expected to have occurred. [Recent work by Romanishin and Angel (1979) shows that the lower mass limit for neutron star formation from single stars (and presumably also wide binaries) is $\geqq 6\ M_\odot$].

In that case the time between the first and second SNE might have been as long as $\sim 2\ 10^7$ yr, in which case the field may have decayed by a factor of order 10^1–10^2.

Therefore, the real puzzle does not seem to be why the binary pulsar has such a low field strength, but why such an old pulsar is spinning so fast.

4. Origin of the Short Pulse Period of PSR 1913+16

Smarr and Blandford (1976) have suggested that the rapid rotation of this neutron star is due to the heavy accretion which it underwent during the X-ray binary phase and the subsequent spiral-in phase (stage *f–g* in Fig. 1). Indeed, many pulsating X-ray binaries are observed to be rapidly spinning up (cf. Schreier, 1977). The rotational history of the first neutron star born in a massive binary system is expected to be composed of roughly the following three stages (cf. Illarionov and Sunyaev, 1975; van den Heuvel, 1977):

a) spin-down, due to emission of a relativistic wind and subsequently by friction against the wind of the main-sequence companion. During this stage no accretion can take place.

b) an equilibrium phase, when the pulsar has been spun down so far that accretion from the weak wind of the main-sequence companion becomes possible. The pulsar then settles at equilibrium spin period

$$P_{eq} \simeq 1\overset{s}{.}6 \left(\frac{B_0}{10^{12}\text{ G}}\right)^{6/7} \left(\frac{R}{10^6\text{ cm}}\right)^{18/7} \left(\frac{M_\odot}{M}\right)^{5/7} \left(\frac{10^{17}\text{ gs}^{-1}}{\dot{M}_a}\right)^{3/7} \tag{2}$$

which is determined by the condition that the co-rotation radius R_c should equal the Alfvèn radius R_A (Davidson and Ostriker, 1973). As long as the companion is on the main-sequence, P_{eq} is expected to be of order 10^2 s (van den Heuvel, 1977).

c) the phase as a strong X-ray source, when the companion star has left the main-sequence and the accretion rate increases rapidly, especially after the beginning of Roche lobe overflow. According to Eq. (2) the equilibrium spin period then rapidly decreases and, due to the accreted angular momentum, the pulsar is spun-up back to a short pulse period.

Indeed, the strong pulsating sources Cen X-3 and SMC X-1 ($P=4\overset{s}{.}84$ and $0\overset{s}{.}71$, respectively) which are believed to be accreting from a disk fed by beginning Roche lobe overflow (Savonye, 1979), are observed to be spinning up on timescales of the order of 10^3 yr. Especially the case of SMC X-1 shows that during this spin-up very short rotation periods can be reached. The minimum spin period that can be reached during the X-ray stage and the subsequent spiral-in is expected to be determined, according to Eq. (2) by the maximum accretion rate that can be reached during these stages (together with the surface dipole field strength). That maximum rate is set by the Eddington limit

$$L_{\mathrm{edd}} = 10^{38.5} \left(\frac{M}{M_\odot}\right) \text{ erg/s}$$

which yields

$$\dot{M}_{a,\max} \simeq 7\ 10^{17} \text{ g/s}.$$

The corresponding equilibrium spin period for $M=M_\odot$, $R=10^6$ cm is:

$$P_{eq}(L=L_{\mathrm{edd}}) \simeq 0.04 \text{ s} \quad \text{for} \quad B_0 \simeq 3\ 10^{10} \text{ G}$$

$$0.75 \text{ s} \quad \text{for} \quad B_0 \simeq 10^{12} \text{ G}.$$

One notices that the equilibrium spin period for $B_0 \simeq 3\ 10^{10}$ G is close to the observed spin period $P_p = 0\overset{s}{.}059$ of PSR 1913+16 (especially if one takes into account that $R/10^6$ cm and $M/M_\odot$ may be slightly different from unity).

We therefore conclude that Smarr and Blandford's (1976) suggestion that PSR 1913+16 is an old neutron star which was spun-up back by the heavy accretion during a spiral-in phase, gives a quantitatively consistent explanation of its combination of low B_0 and short pulse period.

This conclusion is important as it implies that also the companion star of PSR 1913+16 must be a neutron star or a black hole, since otherwise the large orbital eccentricity (0.61) of the system cannot be explained. Because, during the spiral-in phase the large frictional drag will have rapidly removed any orbital

Table 1. Various possible radio pulsars anticipated to be produced by evolution of binary systems (see also Webbink, 1975 and Smarr and Blandford, 1976). ΔM_1 is the combined mass loss from the system during the first stage of mass transfer and the first SN explosion (the latter only for systems with $M_1 \geqq 8 M_\odot$)

	$M_1 \geqq 8 M_\odot$ $M_2 \geqq 9.4 M_\odot - M_1 + \Delta M_1$		$4.7 M_\odot < M_1 < 8 M_\odot$ $M_2 > 9.4 M_\odot - M_1 + \Delta M_1$
Type of binary	Close (case B)	Wide (case C)	Wide (case C)
Lower limit to M_1	$\sim 12 M_\odot$	$\sim 8 M_\odot$	$\sim 4.7 M_\odot$
Intermediate system	Close massive X-ray binary (Cen X-3, 4 U 0900 − 40)	Wide X-ray binary (transient?)	White dwarf + star $\geqq 8 M_\odot$
Final system	Pulsar binary or two runaway pulsars	Pulsar binary or two runaway pulsars	Pulsar plus white dwarf, most probably in a bound system
Type of resulting radio pulsars	Youngest one is "normal", i.e. has a strong field combined with a short pulse period or weak field and long period. Oldest one can be "abnormal" i.e. have a weak field and a short period or a strong field and a long $(>0\overset{\text{s}}{.}5)$ period	The same as for close systems	Pulsar is "normal", i.e. strong field combined with short period or weak field and long period
Alternative outcome	One or both components may be a black hole		

eccentricity that might have been present before this stage. Therefore, the only way to obtain the presently very eccentric orbit is by explosive mass ejection (Boersma, 1961) which means that the companion must have undergone a supernova.

5. Further Constraints on the Progenitor System

Although newborn pulsars cannot have a short pulse period in combination with a weak magnetic field, this does not necessarily mean that a neutron star that was spun back up to a very short pulse period cannot have started out with a rather weak surface field. Because, if its rotation period at birth was ~ 1 s, the dipolar component of its field may have weakened considerably before its crust crystallized (cf. Sect. 3). It is possible that this has happened in some of the massive X-ray binaries, notably in 4 U 0900 − 40 and A 0535 + 26. The pulse structure of these sources has at least four components, suggesting a field at least as complex as a quadrupole. The presence of a massive early-type component in these systems indicates that these neutron stars cannot be older than $\sim 5\,10^6$ yr. Therefore, their field cannot have decayed appreciably since their crust crystallized. The multicomponent structure of their fields might possibly indicate that the dipolar component had time to relax before their crusts froze, which would suggest a rotation period of the order of 1 s at their formation. (An alternative interpretation could be that their surface quadrupole field is very strong, of order 10^{14} G, such that their far field would still resemble that of a $>10^{12}$ G surface dipole field). If this is true, PSR 1913 + 16 may well have descended from a massive X-ray binary like 4 U 0900 − 40, and its true age may be $\leqq 10^7$ yr.

Alternatively, a descendence from a somewhat lower-mass system, with initial components of order 8 $M_\odot$ cannot be ruled out and in that case the weak present field may be due to decay during the rather long time elapsed between the first and the second SNE (cf. Sect. 3). On the other hand, Cen X-3 and SMC X-1 have a simple double pulse structure and the surface dipole components of their fields must be $\geqq 10^{12}$ G. These sources are thought to be spinning near their equilibrium spin periods (cf. the arguments given by Schreier, 1977). Then Eq. (2) in combination with mass accretion rates of $\sim 10^{-9} M_\odot$/yr and $10^{-8} M_\odot$/yr, respectively (inferred from their X-ray luminosities), yields

$$B_0 \simeq 3\text{–}5\,10^{12}\,\text{G for Cen X-3 and } >10^{12}\,\text{G for SMC X-1.}$$

Consequently, a spiral-in evolution of these systems is expected to result in a strongfield old pulsar with a spin period not much shorter than about 0.5 s (cf. Sect. 4), i.e. very different from PSR 1913 + 16.

As the disruption probability of the system in the second SNE is quite large (Flannery and van den Heuvel, 1975), the second SNE will either produce a binary pulsar or two runaway pulsars. Table 1 summarizes the various possibilities for the final evolution of high and intermediate mass close binaries and the resulting ways of formation of binary and runaway pulsars, as outlined above (see also Webbink, 1975 and Smarr and Blandford, 1976). The absolute lower limit to M_1 of 4.7 $M_\odot$ results from the fact that after the first stage of mass transfer the mass of the secondary should be $\geqq 8 M_\odot$ in order to produce a pulsar (throughout the table, the mass of a neutron star is assumed to be 1.4 $M_\odot$).

6. Conclusions

(i) The combination of short pulse period and low surface dipole field strength observed in PSR 1913+16 is excluded for a young radio pulsar (age $\leqq 5.10^6$ yr).

(ii) The low galactic latitude ($z \leqq 200$ pc) and high orbital eccentricity indicate that less than a few times 10^6 yr ago a supernova explosion must have taken place in the system. Since PSR 1913+16 cannot be the remnant of this explosion, its companion must also be a neutron star (or black hole).

(iii) The (P, B_0) combination of PSR 1913+16 strongly suggests a spiral-in history, during which an old pulsar was spun up back towards a short pulse period, by accretion. Its present pulse period is close to the shortest possible pulse period expected in such a case.

(iv) The progenitor system may either have been a massive X-ray binary like 4U 0900−40 or an intermediate mass binary, with initial component masses $\sim 8\,M_\odot$.

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