Reprinted from Current Science December 5, 1982, Vol. 51, No. 23, 1096–1099

ON THE ORIGIN OF THE RECENTLY DISCOVERED ULTRA-RAPID PULSAR

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ABSTRACT

The rapid rotation rate of $\sim$ 1.5 ms of the newly discovered pulsar PSR 1937 + 21 is attributed to spin-up in a long-lived mass transfer binary. Such a history leads to a prediction of a very low period derivative $\sim 6 \times 10^{-19}$ ss^{-1} for this pulsar. The gravitational radiation from this pulsar is expected to be negligible.

BACKER *et al.*[1] have recently announced the detection of a pulsar at the position of the source 4C 21.53 with the remarkably short period of 1.557708 ms. They have also mentioned an estimate for the period derivative of 3×10^{-14} ss^{-1}, which value however, is understood to be uncertain (private communication, W. M. Goss). Even so, the extraordinarily rapid rotation of this pulsar enables us to make a number of observations regarding its possible origin and attributes. We find that the most plausible origin for its present short period is as a recycled neutron star previously in an accreting x-ray binary system.

Assuming for the moment the value of $\dot{P}$ as given by Backer *et al.*[1] this would imply a *maximum* age of $\sim$ 750 y for the pulsar to have slowed down to its present period from 0.5 ms which is close to the shortest possible initial period. This would suggest that the age of this pulsar is less than that of the Crab, the youngest known so far. Barring for the moment the possibility that the neutron star was created in an unorthodox fashion (which we discuss later), there are serious difficulties with assuming that it is only its ultra rapid rotation which distinguishes it from the Crab and the majority of other pulsars.

If it had been born in a supernova explosion which took place within the last 800 y or so, it is most surprising that no strong supernova remnant has been catalogued in this direction. Nor can we suppose that the explosion was so recent (less than say 50 y) that not enough interstellar matter has been swept up to create a turbulent shell which emits in the radio; we could then ask why the explosion was not observed, since the distance estimated from the dispersion measure is $\sim$ 2 kpc, equal to or less than the distance to any of the several historically observed supernovae[2].

It could be claimed that there is no definite evidence that all supernovae leave behind radio remnants, and that very little mass was ejected by this explosion for reasons perhaps connected with the extremely short period of this pulsar. But whatever the reasons for the absence of a shell remnant, it is much harder to explain the absence of a Crab-like remnant or plerion that should have been created by this pulsar. If the period derivative were in fact 3×10^{-14} ss^{-1} (corresponding to a field of 2.3×10^{11} G), the rate at which energy in particles and magnetic field is being deposited into the interstellar medium is 3.10^{41} ergs s^{-1} or a thousand times greater than the Crab pulsar rate. Depending on the length of time for which this has been happening, a respectable and observable nebula should have been found at this position assuming here that the energy loss is mainly due to electromagnetic processes and not gravitational radiation. (We discuss the latter possibility later.)

Although strong radio emission from such a nebula requires sufficient time for the accumulation of enough relativistic particles in it, the x-ray emission from it will be more closely linked to the present energy output of the pulsar, because of the short radiative lifetime of the particles involved[3]. If we use the Crab as a model, we should therefore expect a thousand times stronger x-ray emission from the vicinity of this pulsar which is approximately at the same distance. However, searches by Uhuru and other satellites which covered the position of the rapid pulsar show no source greater than $\sim 1\ \mu$Jy in the energy range 2–6 KeV[4,5]. This limit is $10^3 - 10^4$ less than that from the Crab nebula as a whole. According to present wisdom, this fact would be more consistent with a period derivative for the pulsar of less than 10^{-19} ss^{-1} (corresponding to a field of $< 4 \times 10^8$ G). Although this value might appear to be very small, we would like to point out that it implies an energy output of $\sim 10^{36}$ ergs s^{-1}, comparable to that of the Vela pulsar. Pending a definitive determination of this parameter, we shall assume that $\dot{P}$ is less than the above low value and discuss some consequent implications.

We now turn to the optical emission to be expected from this pulsar. If we assume as we did for x-rays above, that the pulsed optical emission scales with the energy output, we can estimate the apparent magnitude of this pulsar. If $\dot{P} = 3 \times 10^{-14}$ ss^{-1}, this would lead one to expect a star brighter than 11th magnitude, allowing for extinction of 2 mag but ignoring the possible increased efficiency of synchrotron output with decreasing period[6]. However, an examination of the Palomar prints shows no object brighter than 17th or 18th magnitude close to the position of the pulsar given by Backer *et al.*[1] On the other hand, if $\dot{P} \sim 10^{-19}$ ss^{-1} as inferred above, one can use the formula given by Pacini[6] to estimate the strength of the optical emission. Such an estimate leads one to expect a star fainter than 25th magnitude.

The measured period ($\sim$ 1.5 ms) and the limits on its derivative $\sim 10^{-19}$ ss^{-1} inferred as above, would lead to an estimate of the surface magnetic field of a value as low as $\sim 4 \times 10^{8}$ gauss. This is several orders of magnitude below the fields in the Crab and Vela pulsars, which are believed to be reasonably young and are both associated with SNRs. If pulsar PSR 1937 + 21 had had a conventional history, it would mean that pulsars could have very low fields at birth ($< 10^{9}$ G); but such neutron stars will also have to have very short periods ($<$ 20 ms) to produce enough voltage to function as pulsars[7]. It appears to us much more reasonable to assume that both the very short period and the very low field have a common cause which is relatively rare.

The case of pulsar PSR 1937 + 21 is more reminiscent of that of the binary pulsar PSR 1913 + 16, which has a short period (59 ms), a weak field (3.10^{10} G), and no SNR associated with it. The latter case is now well understood as having resulted from spin-up during an x-ray phase in a close binary system with the weak field accounted for by age and magnetic decay[8,9]. The justification for invoking a non-standard history for this pulsar is found in the work of Flowers and Ruderman[10] on the origin and stabilisation of pulsar magnetic fields. Based on considerations of the magnetohydrodynamical and crust crystallization timescales, they argued that low magnetic fields at birth are possible only for relatively long initial periods ($P_0 > 0^{s}.5$). Fast pulsars on the other hand will retain the fields resulting from adiabatic compression in the precollapse core. It was shown[9] that the present period and magnetic field of PSR 1913 + 16 are consistent with spin-up to an equilibrium value corresponding to the strength of the magnetic field at the time of maximum accretion. The longer the evolution time for the secondary in the binary system, the greater will be the decay of the field of the first born neutron star, and the shorter will be the period to which it is spun-up. For such recycled pulsars, which become observable after the second explosion in the binary system, it is to be *expected* that very small period derivatives will be associated with very short periods, as opposed to the case of ordinary pulsars where the reverse is true. At least two other pulsa·s, PSR 1804-08 and PSR 1541-52, have been suggested as examples of pulsars recycled in binary systems, but which were disrupted by the second explosion unlike the case of the binary pulsar PSR 1913 + 16[11]

If we suppose that the present pulsar also acquired its rapid rotation through spin-up in a binary system, the field-period equilibrium condition referred to earlier[9] would require that its present magnetic field be less than 10^{9} G and that its present $\dot{P}$ should therefore be less than 6×10^{-19} ss^{-1}. (We have taken $M = 1.4\, M_{\odot}$ and $R = 10^{6}$ cm.) These limits are on the assumption that the spin-up was in the recent past. But it could well have been in the distant past, in which case the limits are even stronger. In any case, if we assume that the initial magnetic field of the pulsar at birth was comparable to that of the Crab and Vela pulsars, then the present field (deduced as above) represents a decay by a factor of $\sim 4 \times 10^{3}$. If we assume an exponential decay time for pulsar magnetic fields of 2.10^{6} y as estimated by Radhakrishnan[12], this would imply an evolution time of $(1 - 2) \times 10^{7}$ y for the secondary star. A time of this order, while longer than the usual time of a few million years for massive close binaries is of the right order for lower mass systems[13]. In the present context, the relative rarity of such systems remaining bound after the first explosion[13,14] is consistent with the rarity of such extremely short-period pulsars.

An alternative scenario to explain the combination of a short P and low B has been provided by a number of recent developments in stellar evolution relating to SN explosions in accreting white dwarfs. If the mass of the primary in a close binary system is in the narrow range of ~ 8–$10\, M_{\odot}$ it is expected to end up as a O-Ne-Mg white dwarf after the second stage of mass transfer (see Nomoto[15], and references therein). It has been argued further that when the secondary star evolves away from the main sequence and begins to transfer mass back on to the white dwarf, the latter may be driven over the Chandrasekhar limit and undergo an electron capture SN leaving behind a neutron star.

The calculations by Nomoto[15] show that at the time of the collapse, the core will have a radius of $\sim 10^{2}$ km and a density $\sim 2.5 \times 10^{10}$ g cm^{-3}. It has also been shown recently[16], that only 3-5% of white dwarfs have surface magnetic fields $> 3 \times 10^{6}$ G. If we assume that the O-Ne-Mg white dwarf had a field of this order, the above scenario will yield on collapse a field of a few times 10^{8} G for the neutron star. To explain the observed period of $\sim$ 1.5 ms for the pulsar, the core of the white dwarf should have been spinning with a period ~ 0.15 s. Such a fast period does not appear to us to be ruled out, particularly in an accreting system. van den Heuvel[13] has remarked that only a small fraction of the many O–Ne–Mg white dwarfs in *close* binary systems are likely to become SN. He has further emphasized, that since the mass ejected in the collapse of such a white dwarf will only be a few tenths of a solar mass, the system is likely to be disrupted only in rare cases. The rarity of objects like PSR 1937 + 21 is therefore not inconsistent with such a possible origin.

Another interesting aspect on which light is thrown by the very rapid rotation of this pulsar is gravitational radiation. In a discussion on the various modes of energy loss possible for young (and therefore presumably fast) pulsars, Ostriker and Gunn[17] have suggested that gravitational radiation might be the main channel at very short periods. On this assumption they have shown that the discrepancy of $\sim 25\%$ between the true age of the Crab pulsar, and that derived from P and $\dot{P}$, can be explained as due to gravitational radiation which dominated for the first 80 years or so. According to them, this would have required an equatorial 'ellipticity' of 3×10^{-4} in the shape of the neutron star to provide the quadrupole moment responsible for the radiation. A limit on the corresponding quantity for PSR 1937 + 21 can be obtained by assuming that *all* of the present energy loss is due to gravitational radiation. Taking $\dot{P}$ to be 3.10^{-14} ss^{-1}, we obtain an ellipticity of $< 2 \times 10^{-6}$, considerably less than that above. If $\dot{P}$ is in fact closer to 6×10^{-19} ss^{-1}, the corresponding limit on the ellipticity will be consequently reduced to $< 10^{-8}$.

We could also ask what ellipticity may be expected for the equatorial plane. The large rotational distortion of longitudinal sections of course leads to no gravitational radiation. If the equatorial ellipticity is produced entirely by the present magnetic field estimated earlier to be $< 10^{9}$ G, we would expect a value $\sim 10^{-17}$ [equation (A27) of Ostriker and Gunn[17]], and gravitational radiation would be totally negligible. However, if there is an equatorial ellipticity "frozen in" from an earlier epoch, it could be as large as 10^{-6} and mainly responsible for a $\dot{P}$ as large as 3×10^{-14} ss^{-1} without being inconsistent with available observations. The luminosity of the gravitational radiation in this limiting case would be $< 10^{41}$ erg s^{-1}, and represents an interesting upper limit from the point of view of developing detectors for this radiation. (We thank J. P. Ostriker for a discussion leading to the conclusions in this paragraph).

To sum up, the very short observed period of the pulsar and the absence of a radio or x-ray SNR at its position lead us to the following tentative conclusions.

The history of this pulsar was certainly different from that of the majority of other pulsars. It could have been created by accretion on to an O–Ne–Mg white dwarf in a binary system. However, we propose that:

1. It acquired its rapid rotation rate as a *neutron* star in an accreting binary system in which the evolution time for the secondary was $(1-2) \times 10^{7}$ y. During this time, its initial field decayed to $\sim 10^{9}$ G and led to an equilibrium period of ~ 1.5 ms during accretion.
2. The disruption of the binary system by the second explosion in it took place at least several thousands of years ago, so that the remnant has been completely dispersed in the ISM. The companion neutron star would have moved away in distance by an amount proportional to this unknown time, and may or may not be observable.
3. Since the present magnetic field can be no greater than the field at accretion time, the present period derivative, according to this scenario must be considerably less than 3.10^{-14} ss^{-1}. It is thus a prediction and a test of this hypothesis, which must be rejected if an accurate determination of $\dot{P}$ shows it to be closer to 3.10^{-14} ss^{-1} than $\sim 10^{-19}$ ss^{-1} which we expect.
4. If $\dot{P}$ is indeed of the order we expect, it is an interesting fact that the limiting rotational period of this *neutron* star as $t \to \infty$ will be longer than the present period by only a few parts in a thousand. Pulsar activity, on the other hand, will have ceased by the time the field has decayed to $< 10^{7}$ G.
5. Even at such a rapid period, the ellipticity expected from stresses due to the magnetic field we deduce will be so small as to make gravitational radiation of no significance. Frozen-in distortion, however, could be much larger and contribute significantly to braking due to gravitational radiation.

Acknowledgements

We are very grateful to W. M. Goss for information regarding observations of this pulsar. We thank T. M. K. Marar, C. R. Subrahmanya and B. R. Iyer for discussions on various topics, and the referee for several comments which helped to improve this paper.

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