ON THE IMPLICATION OF THE RECENTLY DISCOVERED 5 MILLISECOND BINARY PULSAR PSR 1855+09

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ABSTRACT

We argue that the extraordinary fact that all three known millisecond pulsars are very close to the galactic plane implies that there must be ~ 100 potentially observable millisecond pulsars within ~ 4 kpc from the Sun. Our other main conclusion is that the dipole magnetic fields of old neutron stars probably saturate around 5×10^8 gauss.

I. INTRODUCTION

ONE of the unsolved puzzles about the two fastest pulsars, the 1.5 ms pulsar (PSR 1937 + 21) and the 6 ms binary pulsar (PSR 1953 + 29) concerns their location: *why are these two pulsars, which must surely be very old, so close to the galactic plane*? The recent discovery[1] of a 5 ms binary pulsar PSR 1855 + 09, again very close to the plane, underscores this puzzle. We address this question and its implications in this article. Table 1 summarizes some of the relevant parameters of these three pulsars.

II. PROGENITORS OF MILLISECOND PULSARS

It is now widely accepted that millisecond pulsars must have been spun up in mass transfer binary systems[2-4]. If one grants that the neutron star accretes from its companion at the Eddington rate for sufficiently long, then it can be spun up to ultra-short periods. The observed P and $\dot{P}$ for the 1.5 ms pulsar and the 6 ms pulsar are consistent with this picture. Even though there is as yet no consensus on the details of such a recycling scenario for the 1.5 ms pulsar[3,4], the picture is much clearer for the 6 ms pulsar which is still in a binary. It has been very convincingly argued by Joss and Rappaport[5] that the progenitor for this latter system must have been a low-mass X-ray binary (LMXB); many such systems are known in our galaxy. These are believed to consist of neutron stars accreting from low mass giants. As they have argued, in such systems there is no difficulty in maintaining mass transfer at close to the Eddington rate for as long as $\sim 10^8$ years or more.

PSR 1855 + 09: Drawing from the detailed work of Webbink *et al*[6], we wish to suggest that this pulsar, too, must have evolved from an LMXB. An initial orbital period ~ 1 day would lead to the presently observed orbital period of 12.33 days. In this case the mass transfer probably lasted for $\sim 10^9$ years, implying that this pulsar must be even older than PSR 1953 + 29.

Why are all these three very old pulsars so close to the galactic plane? "Normal" pulsars have a scale height[7] ~ 350 pc, much larger than the scale height of their progenitors, which is only ~ 60 pc. This is easily understood if neutron stars acquire substantial velocities at birth. Even if millisecond pulsars are not created with such velocities, one would expect them to have a scale height at least comparable to that of their progenitors.

As already mentioned, the progenitors of millisecond pulsars, at least those which are in binary systems, must be LMXBs. Presently about 30 LMXBs are known in our galaxy and the total number [8-10] is probably ~ 100. The 20 or so sources for which reasonably accurate distances are known clearly reveal that they have a scale height ~ 300 pc, consistent with their belonging to the old disk population. It is, therefore, extraordinary that all three millisecond pulsars discovered are within ~ 25 pc of the galactic plane.

III. POSSIBLE WAYS OUT

This remarkable "coincidence" could in principle be rationalised under two exotic circumstances:

(a) The scale height of the very old neutron stars previously associated with LMXBs is indeed large, but for some reason they do not function as pulsars unless they are in an environment that obtains only very close to the galactic plane.

(b) For some unknown reason, the velocity dispersion

Table 1 *The millisecond pulsars*

Pulsar	Spin period (ms)	Magnetic field (10^8 gauss)	Orbital period (days)	Most likely companion mass ($M_\odot$)	Distance (kpc)	z* (pc)	Ref.
1937+21	1.55	4.5	—	—	~3–5	~ −20	(a)
1953+29	6.13	4.5	117.3	0.2–0.5	~3	~24	(b)
1855+09	5.36	—	12.33	0.25–0.6	~0.4	~24	(c)

(a) Backer, D. C. 1984, *J. Astrophys. Astron.*, **5**, 187
(b) Rawley, L. A. et. al. 1986, *Nature*, (*London*), **319**, 383
(c) Segelstein, D. J. et. al. 1986, IAU Circ. no. 4162
*Distance from the galactic plane

of these old pulsars *decreases* with time and they "settle down" near the plane.

At present we have no suggestions to offer concerning either of these possibilities. This leaves us with only one alternative: The proximity of the three known millisecond pulsars to the galactic plane is accidental, or possibly due to selection effects which we do not understand. If so, an immediate implication of this is that the sample of millisecond pulsars must be grossly incomplete even within the distances upto which they have been found. If the scale height for these pulsars is ~300 pc, like the LMXBs from which they must have come, then one would expect only ~10% of them to be within ~30 pc from the galactic plane.

This suggests that there should be at least ~30 millisecond pulsars in the region in which the three known pulsars lie, namely between the galactic longitudes 30° and 90° and within ~4 kpc from the sun. This implies that within the above distance from the sun, there should be at least ~10^2 millisecond pulsars. This number must surely be a lower limit since it does not allow for the beaming factor of pulsars (taken to be ~5 for circular beams) and various other selection effects due to dispersion and luminosity which are likely to be severe for ultrafast pulsars. Taking a conservative attitude, it is reasonable to speculate that there should be $\gtrsim 3 \times 10^2$ millisecond pulsars within about ~4 kpc, implying a total number in the galaxy $\gtrsim 2 \times 10^3$.

This number is clearly discrepant with the number of LMXBs in the galaxy. As already mentioned, the number of LMXBs is not expected to be much larger than ~100. Our basic premise, namely that these millisecond pulsars evolve from LMXBs, then implies that their lifetimes must be 20–30 times longer than the X-ray phase of these systems, which are believed to last for ~10^8 years. We thus conclude that millisecond pulsars must live for $\gtrsim 10^9$ years.

IV. FIELD SATURATION

We shall now argue that such long lifetimes are possible for pulsars only if their magnetic dipole moments, after an initial decay, essentially saturate. It is possible to obtain a lower limit for the decay timescale of the dipole field in the following manner. It is now generally accepted that millisecond pulsars make their appearance in the B–P plane along the so-called "spin-up" or "equilibrium period" line ($P \propto B^{6/7}$)[4]. They will die when they cross the "death line" ($P \propto B^{1/2}$)[11,12]. From figure 1 it is clear that a pulsar spun up to the shortest period will have the longest lifetime, and will therefore give a lower limit to the timescale of possible field decay. The standard dipole braking law together with an exponential decay of the surface dipole field (with timescale τ_d) yields for the lifetime of a 1 ms pulsar

$$t \approx 4.2 \times 10^9\,\text{yr}\,\tau_d'\ln\left[\left\{1 + \sqrt{1 + 10^{-6}\,\tau_d'(1+\tau_d')}\right\} \times (1+\tau_d')^{-1}\right]$$

where $\tau_d' = \tau_d/(6.2 \times 10^8\,\text{yr})$

From the above equation, it follows that a lifetime $t > 10^9$ years is possible only if $\tau_d \gtrsim 10^9$ years. It will be recalled that the statistics of normal pulsars strongly suggest that their magnetic fields decay with a characteristic time ~a few million years[13]. The apparent 1000-fold lengthening of the decay timescale is perhaps indicative of field saturation around $B \lesssim 10^9$ gauss. van den Heuvel, van Paradijs and Taam[14] have also recently arrived at the conclusion that fields must saturate from a similar argument, but they estimate the total number of millisecond pulsars in the galaxy from a different viewpoint. Motivated by the very large apparent age of the white dwarf companion of the binary radio pulsar PSR 0655+64, Kulkarni[15] has advocated that magnetic fields of neutron stars must eventually saturate.

An independent argument: As was mentioned in the beginning, it is very probable that the newly discovered millisecond pulsar evolved from a low mass X-ray binary with an initial orbital period $\lesssim 2$ days. The mass transfer in a system with such initial conditions lasts for almost $(6\text{–}10) \times 10^8$ years at a rate $\lesssim 10^{-9}$ $M_{\odot} yr^{-1}$, which is smaller than the Eddington rate for a standard neutron star. Consequently, when the binary finally detaches, the neutron star could be almost $\sim 10^9$ years old. This poses a problem: how come such an old neutron star still has a substantial field to enable it to function as a pulsar. The simplest explanation is that its field must have saturated.

While discussing the evolutionary scenario for the 6 ms pulsar, and faced with a similar difficulty, van den Heuvel and Taam[16] suggested that the neutron star was formed by the accretion induced collapse of a white dwarf. This way the age of the neutron star needs to be only a fraction of the duration of the mass transfer phase, and the problem mentioned above may not arise. However, such an alternative may not work in the case of the present system. It is believed that at the relatively low accretion rate mentioned above, nova eruptions will prevent the white dwarf from approaching the Chandrasekhar limit[17]. If so, the neutron star must indeed be very old and one is therefore forced to conclude that the field must have saturated.

Flowers and Ruderman[18] have argued that the current loops in the superconducting interior of the star are stabilised against rearrangements by currents flowing in the crust. Since the crustal current is likely to decay due to ohmic dissipation in a timescale of a few million years, the decay of the dipole field takes place over the same timescale. It is not at all clear what the final value of the dipole field will be after a sufficiently long time. We feel that the dipole field will eventually saturate at some value, and this will be the same for all neutron stars. It is extraordinary that the recent measurement[11] of $\dot{P}$ for the 6 ms pulsar yields a value for its surface magnetic field which is almost identical to that of the 1.5 ms pulsar. Since the 6 ms pulsar is so far from the spin up line (figure 1), we feel that this cannot be a coincidence, and $\sim 5 \times 10^8$ gauss may be the sort of field strength at which the dipole fields of neutron stars saturate. If the magnetic field of the newly discovered pulsar PSR 1855+09 also turns out to be the same it will provide strong support for our conjecture. It is interesting that in an attempt to model superhigh energy radiation from old neutron stars in accreting binary systems, Ruderman[19] has suggested that their magnetic fields may be $\sim 10^8$ gauss. The recently discovered Quasi-Periodic Oscillations in some LMXBs may also be providing independent evidence that the neutron stars in them have a magnetic field $\gtrsim 5 \times 10^8$ gauss[20,21].

If the above conjecture is true, then it has a very interesting consequence for the evolution of pulsars processed in LMXBs. Let us assume that the duration of the mass transfer is longer than the time it would take for the dipole field to decay to its saturation value. This will probably be the case for all LMXBs with initial orbital periods $\leqslant 10$ days,[6] and if the decay time for the magnetic field continues to be ~ a few million years till the field saturates. The neutron stars in such systems will be spun up to some point along the equilibrium period line and then they will dribble down along this line till a limiting period ~ 1.5 ms is reached, corresponding to field saturation around $\sim 5 \times 10^8$ gauss. After the mass transfer stops, and the neutron star starts functioning as a *pulsar*, its evolution will be *sideways*, i.e. the period will lengthen, as shown in figure 1. But given the age of the galaxy, the

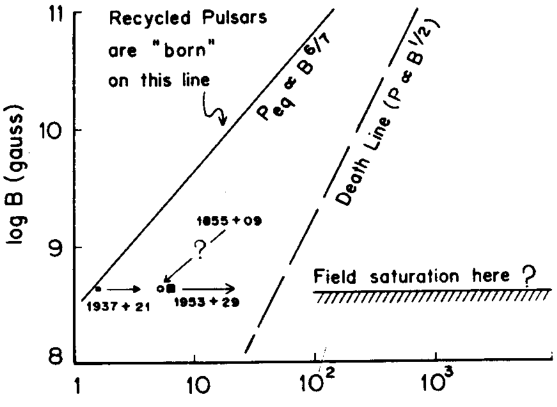

Figure 1. The derived magnetic fields of the 1.5 ms pulsar (1937+21) and the 6 ms pulsar (1953+29) are shown. Also plotted are the "spin-up" line corresponding to the critical accretion rate ($\dot{M}_{\text{Eddington}}$) and the "death line" for pulsars. It is suggested that the magnetic fields of all old neutron stars, including that of PSR 1855+09, will be $\sim 5 \times 10^8$ gauss. The horizontal arrows represent the future evolutionary tracks of these pulsars.

maximum period reached will only be ~ 10 ms. Since $\frac{dP}{dt} \propto \frac{1}{P}$, there will be a "piling up" of these pulsars near $P \leqslant 10$ ms. The fact that two of the three millisecond pulsars discovered so far have period ~ 6 ms is not inconsistent with the above picture.

V. CONCLUSIONS

1. The fact that all three known millisecond pulsars are so close to the galactic plane can only be a "selection" effect. Millisecond pulsars must have a scale height comparable to that of LMXBs from which they probably evolve and we predict that there should be ~ 100 potentially observable millisecond pulsars within ~ 4 kpc.
2. Such a large number of millisecond pulsars is consistent with the birthrate of LMXBs only if the lifetime of these pulsars is more than $\sim 10^9$ years. This, in turn, would require that their magnetic fields do not decay indefinitely, but saturate.
3. We predict that such a saturation occurs around $\sim 5 \times 10^8$ gauss. This will be confirmed if the newly discovered pulsar turns out to have its field near this value.
4. We also predict that the majority of ultrafast pulsars will have periods in the interval 6–10 ms.

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