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The Progenitors of Pulsars

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1. Introduction

This is not only the Diamond Jubilee of the Indian Academy of Sciences but also the Diamond Jubilee of the publication of the prophetic paper by Baade and Zwicky (1934) in which they suggested a possible connection between the supernova phenomena and the formation of neutron stars. Sixty years later the mechanism suggested by them is still the most convincing one for the majority of supernovae. Since this is the only talk in this symposium focussing on the progenitors of pulsars some general remarks may be appropriate. Let us first recall the main conclusions in this regard from stellar evolution theory. These may be summarized as follows:

Stars with $M < 1.4M_\odot$ will definitely end their lives as white dwarfs. In recent years one has come to appreciate that stars as massive as $5 - 6M_\odot$ may also leave behind white dwarfs. Although the upper mass limit for the formation of white dwarfs is still not known with certainty, observations of white dwarfs in open clusters suggest that this mass limit may be as high as $6M_\odot$ (Tinsley, 1977).

According to prevalent opinion some years ago, stars in the mass range $5-8M_\odot$ will ignite carbon in a degenerate core resulting in a total disruption of the star. Indeed this was the popular model for Type I supernovae (Tinsley, 1977). Although considerable uncertainties still surround this scenario there is reasonable agreement that stars in the mass range $8 - 10M_\odot$ will collapse to form neutron star cores due to electron capture instability (van den Heuvel and Habets, 1985). Above, say, $10M_\odot$ stars are expected to form degenerate iron cores which will eventually reach the Chandrasekhar limiting mass for white dwarf configurations and consequently collapse. The result will be the formation of a neutron star and a supernova explosion just as envisaged by Baade and Zwicky. Although the details of how to effectively utilize the binding energy released in the formation of the neutron star to produce a supernova are still not clear, this is the most favoured scenario for Type II supernovae.

Continuing with the theoretical expectations, as one goes to larger masses there must be a critical mass above which degeneracy never sets in however high the density may become. As shown by Chandrasekhar (1932) this happens when the radiation pressure exceeds 9.2% of the total pressure. To quote from

Chandrasekhar's paper:

> *For all stars of mass greater than a critical mass the perfect gas equation of state does not break down however high the density may become, and the matter does not become degenerate. An appeal to Fermi-Dirac statistics to avoid the central singularity cannot be made.*

Stars with masses above this critical mass will presumably find peace as black holes. Given the mass function of stars the majority of the progenitors of neutron stars will have masses close to the lower limit for the formation of neutron stars. One of the things that we wish to estimate is this lower mass limit.

2. Pulsar Birth Rate

The first step towards determining the lower limit to the mass of stars which will leave behind neutron stars is an estimation of the birth rate of pulsars. Before proceeding further let us once again remind ourselves about the observed population of pulars. Fig. 1 shows 560 pulsars with their measured periods and derived surface magnetic fields. One notices that the overwhelming majority of pulsars have fields in the range $10^{12} - 10^{13}$ G.

There are several ways of estimating the birth rate of pulsars. For example, if one is able to derive an *average lifetime* for pulsars then given their total number in the Galaxy one can estimate a mean birth rate. If the birth rate obtained this way has to be reliable it must explicitly allow for the possibility that the birth rate of pulsars with different magnetic fields may not be the same. One of the ways in which this can be allowed for is by calculating the *current* of pulsars (Phinney and Blandford 1981, Vivekanand and Narayan 1981). The current of pulsars along the period axis may be formally defined in analogy with the current of electrons in a wire. Let us consider a period window between P and $P + \Delta P$. The current of pulsars may be defined as follows:

$$J(P) = \frac{1}{\Delta P} \sum_{i=1}^{N_{psr}} \dot{P}_i \tag{1}$$

where the summation is performed over all the pulsars in the period bin. Provided the current in a bin so defined has reached its maximum value it would represent the birth rate of pulsars. (This will be the case if the initial periods of all the pulsars in the population are less than the period chosen and if the death of pulsars is not yet relevant.) Although the above statement is correct in principle one must remember that one has not allowed for the fact that the observed population of pulsars is only a small fraction of the true galactic population. To calculate the true galactic birth rate one has to make two corrections: (1) one must allow for the fact that the radiation from pulsars is "beamed", and (2) one must also account for various *selection effects* which work against the detection of pulsars.

Consider a pulsar with period P and radiation luminosity L. One can compute the probability of detecting such a pulsar in one of the major surveys. Let us define the reciprocal of this detection probability as the scaling factor $S(P, L)$. And let

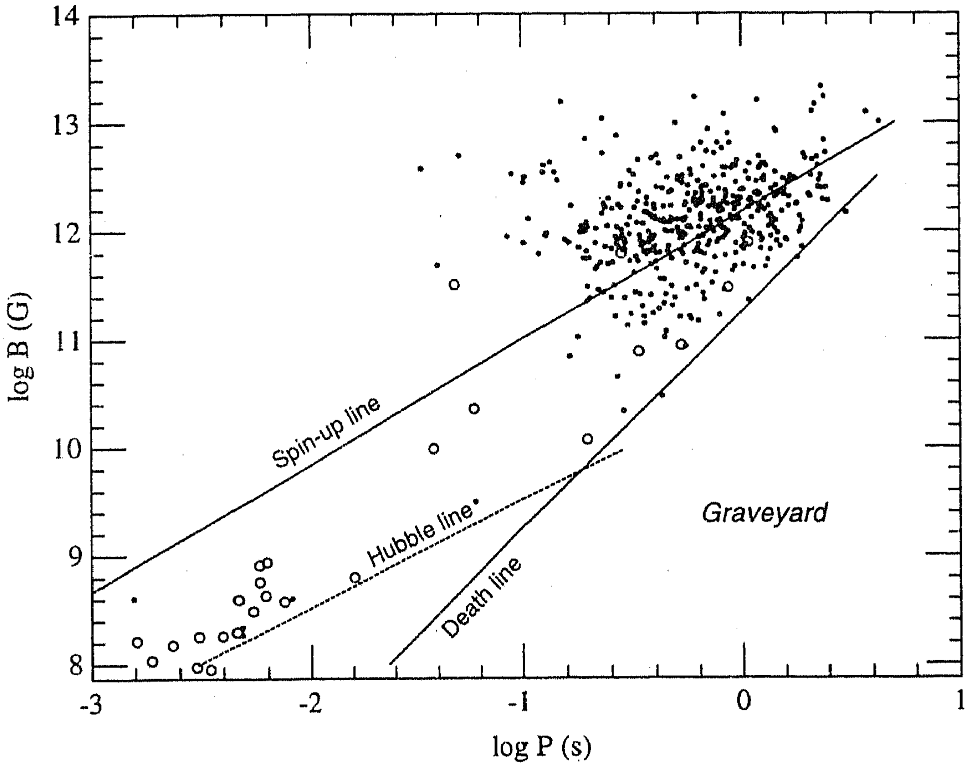

Figure 1: The measured periods and derived surface magnetic fields of 560 pulsars are shown. The pulsar parameters are taken from Taylor et al. (1993).

f be the beaming factor. One can now estimate the true current of pulsars as follows:

$$J(P) = \frac{1}{\Delta P} \sum_{i=1}^{N_{psr}} \frac{1}{f} S(P_i, L_i) \dot{P}_i \tag{2}$$

In practice what one really needs is the scaling factor as the function of P and $\dot{P}$ i.e., $S(P, \dot{P})$ rather than $S(P, L)$. At first sight this may seem like a simple change of variables but it is more subtle than that. One can of course assume an empirical relation between the period and period derivative of a pulsar and its radio luminosity. But one has to allow for the fact that there is a ***distribution of luminosities*** of a given combination of P and $\dot{P}$. Thus in going from the variables (P, L) to $(P, \dot{P})$ one has to average over the probability distribution of luminosities. Such an averaging procedure should not be done after deriving the scaling factor but rather at the level of the more basic quantity viz. the detection probability itself. Although this might seem like a very minor point the conclusions reached can depend upon how the averaging over the luminosities is done (Narayan, 1987; Narayan and Ostriker, 1990).

The current of pulsars calculated in a manner outlined above is shown as a histogram in Fig. 2. It will be seen that the current continues to rise till a period ~ 0.6 s. This clearly points to the fact that not all pulsars are born spinning very rapidly, but there is a broad distribution of initial periods. Beyond this period the

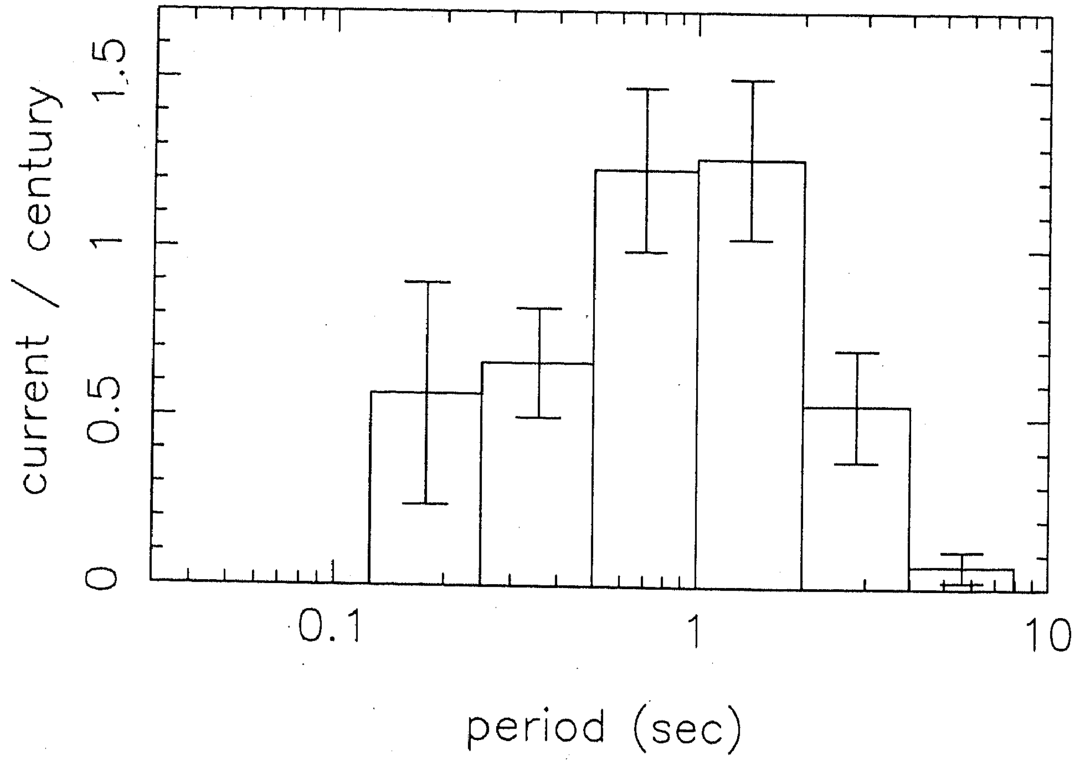

Figure 2: The current distribution as a function of period. As may be seen, the current reaches its maximum value around a period of 0.5 s, and begins to decline at around 2 s. The maximum value of the current corresponds to a pulsar birth rate of about 1 in 75 years.

current is roughly constant till a period ~ 2 s and then begins to decrease due to deaths of pulsars becoming significant. The maximum value of the current yields a pulsar birth rate of ~ 1 in 80 years. This number should be compared with a birth rate of 1 in 100 years derived by Narayan and Ostriker (1990), and also with the estimate of Lorimer et al. (1993) who got a birth rate of 1 in 125 to 250 years for a set of luminosity-limited samples. For a comparison of these birth rates under discussion we refer to Deshpande et al. (1995). It is appropriate to recall that the derived birth rate of pulsars is particularly sensitive to the distance scale to pulsars. In the present analysis we have used the latest distance model due to Taylor and Cordes (1993) for comparison. The previously preferred distance model due to Lyne, Manchester and Taylor (1985) yields a birth rate of 1 in 40 years.

Given a birth rate of pulsars one would of course like to compare it with the supernova rate, as well as the birth rate of supernova remnants. Such a comparison continues to be difficult as in the past. There is still no agreement on the estimated supernova rate in the Galaxy based upon the statistics of supernovae in external galaxies with morphology similar to ours. The estimate of Clark and Stephenson (1977) of 1 in ~ 30 years based upon the historical supernovae recorded in the last two millenia continues to be the only firm estimate.

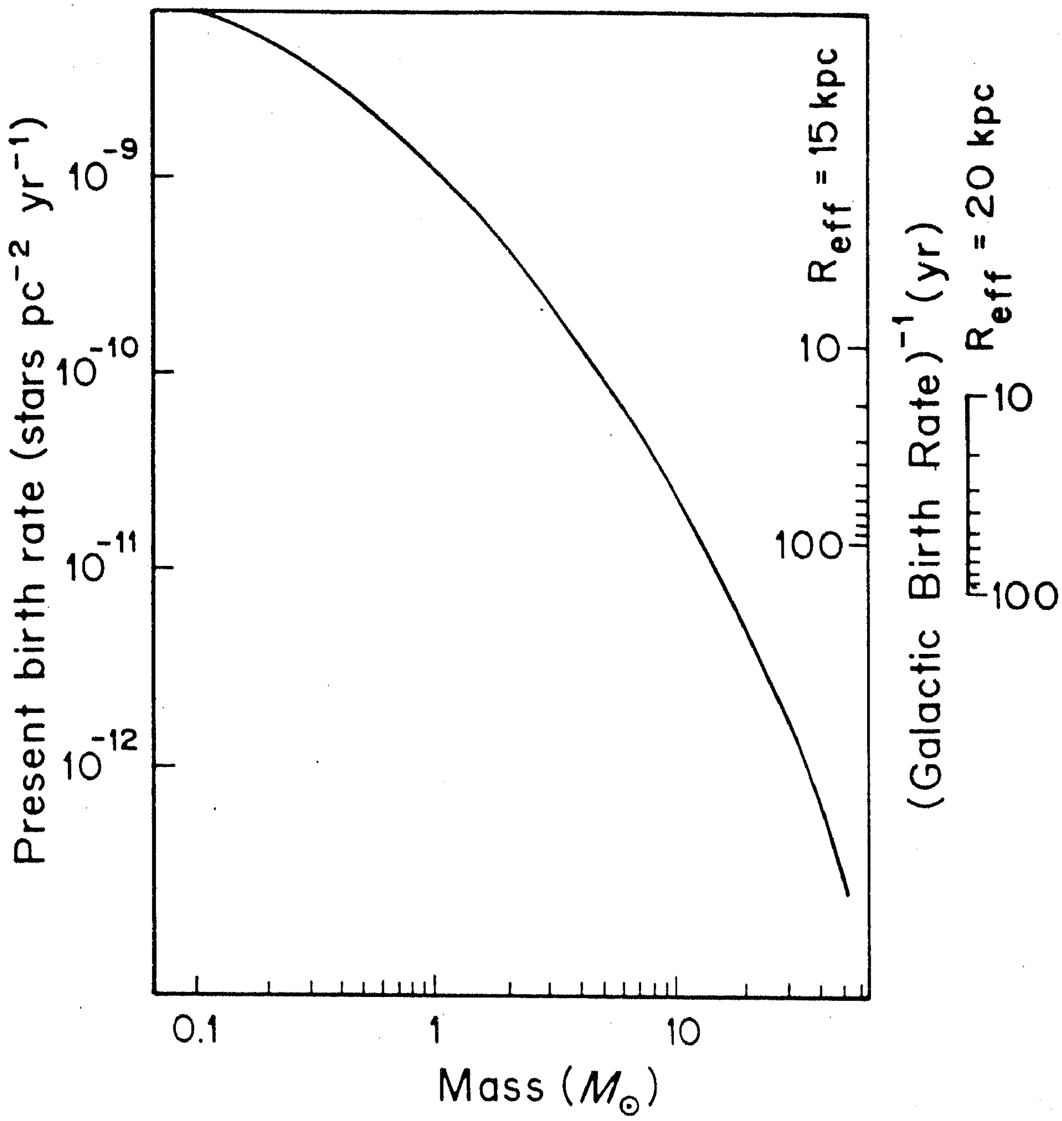

Figure 3: Integrated stellar birth rate as a function of Mass. This has been adapted from Wheeler et al. (1980). On the right hand side we have shown the galactic pulsar birth rate for two assumed effective radii for the Galaxy.

Turning to supernova remnants, an estimate of their birth rate depends critically on the assumed model of the interstellar medium into which they are expanding. In the standard model all supernova remnants are assumed to be in the Sedov or self-similar phase of expansion. If one accepts this for a moment then it yields a supernova birth rate ~ 1 in 120 years (Clark and Caswell, 1976). But this assumption needs to be questioned. The standard model is justifiable in the case of those remnants that have expanded for a long time in a relatively dense interstellar medium with a number density ~ 1 atom/cm^3. However, if the ambient density is much lower then the free expansion phase will last longer, and one would be grossly over-estimating the age of a given remnant if one used the standard model. During the past decade there is growing observational evidence for a much more rarified component of the interstellar medium with a relatively large filling factor (McKee and Ostriker, 1977). If one allows for the possibility that a certain fraction of supernova remnants may be expanding in a rarer component of the interstellar medium then the estimated supernova remnant birth rate will be much higher than that suggested by the standard model. Given all these uncertainties it appears that the birth rate of supernova remnants may be telling us more about the properties of the interstellar medium rather than the supernova rate itself.

After this digression let us return to our discussion of the progenitors of pulsars. Given a reasonable estimate for the pulsar birth rate one should now attempt to define the mass range within which stars end their lives as neutron stars. To do this one must compare the birth rate of pulsars to the death rate of stars. For sufficiently massive stars ($M \gtrsim 3 M_\odot$) their birth rate may safely be assumed to be equal to their death rate. The birth rate of stars can be inferred from star counts and their theoretical lifetimes on the main sequence. But there are some uncertainties in the derived birth rate. For example, the distribution of O and B stars is patchy. Also, star counts are done as a function of spectral types which have to be converted to masses. In addition there is the following complication. The birth rate of pulsars one has derived is a galactic rate, while star counts yield a local rate. If the distribution of pulsars was uniform not only in the azimuthal coordinate but also as a function of galactocentric radius then using the estimated radius of the Galaxy one can convert the galactic pulsar rate to a local birth rate. But there is observational evidence for a gradient in the distribution of supernova remnants, HII regions, giant molecular clouds etc. as one goes away from the inner Galaxy. Therefore, to properly convert a galactic rate to a local rate one must assume a larger *effective radius* for the Galaxy than its actual dimensions. In Fig. 3 we have shown the integrated death rate of stars using the initial mass function due to Miller and Scalo (Wheeler et al., 1980). If one assumes an effective radius for the Galaxy of 20 kpc then a pulsar birth rate of 1 in 80 years implies that all stars with masses above $12 - 15 M_\odot$ should produce neutron stars. On the other hand a pulsar birth rate of 1 in 40 years would require that all stars more massive than $7 - 8 M_\odot$ should leave behind neutron stars.

3. Do pulsars trace spiral arms?

An interesting question related to the minimum mass for the formation of neutron stars is their possible spatial association with the spiral arms of the Galaxy. This question was first explicitly discussed by Blaauw (1985). He, too, was trying to estimate the minimum mass for the formation of neutron stars, but he directly tried to estimate the local birth rate of pulsars by restricting himself to the sample of pulsars whose distances projected on to the galactic plane were less than 0.5 kpc. From information on the scale height of pulsars, their measured proper motions and their mean lifetime he concluded that *the local population of pulsars must be replenished by local progenitors.* He went on to conclude that OB associations cannot by themselves account for the local population of pulsars, and that lower mass field stars in the mass range $6 - 10M_\odot$ must make the major contribution to the pulsar birth rate. If this conclusion is correct then Blaauw argued that "*pulsars are on a galactic scale, tracers of regions of past spiral structure rather than of active spiral structures*". To elaborate on this beautiful point, if the progenitors of the majority of pulsars were the massive OB stars which delineate the spiral arms then one would expect pulsars also to be located close to the leading edge of the spiral arms since massive stars have relatively short lifetimes. But if the majority of progenitors are less massive then, say, $10M_\odot$ then one would expect them to explode at substantial distances from the leading edge of spiral arms. This is because of the relative motion between the spiral density waves and the matter in the Galaxy during the lifetime of the star. Consequently the location of the majority of pulsars should not have any strong correlation with the present spiral pattern.

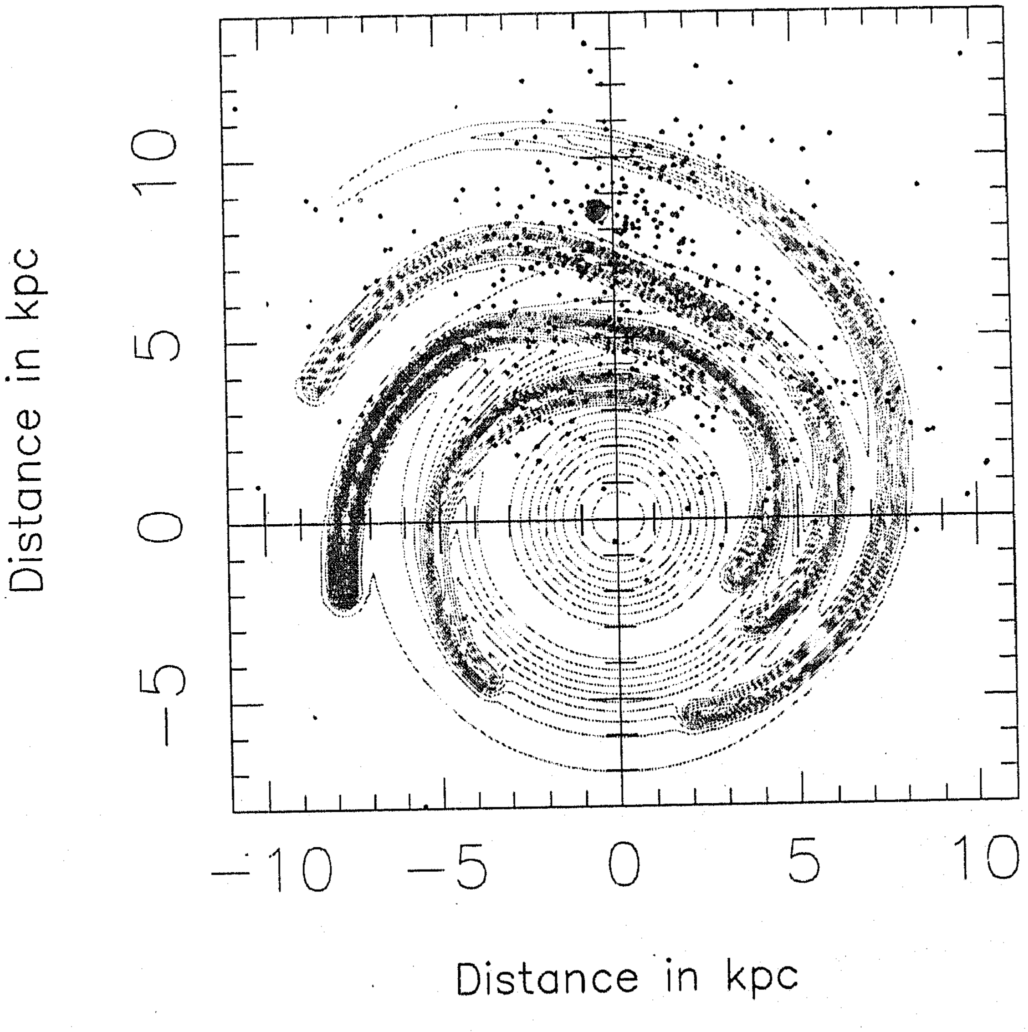

Figure 4: The electron density distribution derived by Taylor and Cordes (1993) is shown as a contour diagram. The *dots* indicate the location of the pulsars estimated from this model and projected on to the plane of the Galaxy.

Does the matter distribution lead the spiral pattern or lag behind it? This depends on the galacto-centric distance. Since the Galaxy is rotating differentially, and the spiral pattern rigidly, inside the *co-rotation radius* R_c the spiral pattern will lag behind the matter, and the converse will be true outside the co-rotation radius. From a detailed dynamical modelling of the gas distribution and their motions in our Galaxy it appears that the co-rotation radius is approximately 12 – 15 kpc (Burton, 1971). Since the majority of pulsars are inside the solar circle their circular velocities should be larger than that of the spiral pattern at the corresponding radius and consequently the present distribution of pulsars should be ahead of the present spiral pattern.

Recently an attempt was made to test this remarkable conjecture by Blaauw (Ramachandran and Deshpande, 1994), viz. one tried to look for a correlation between the present distribution of pulsars and the location of the spiral arms in the past. An essential ingredient in this analysis is the distance estimate to the known pulsars. Like in the birth rate analysis the recent electron density distribution due to Taylor and Cordes (1993) was used. The distribution of pulsars derived from this model and projected on to the plane of the Galaxy is shown in Fig. 4. The *dots* indicate the pulsars and the contours show the electron density distribution. As may be seen, the observed density of pulsars is systematically higher in the solar neighbourhood as might be expected from various selection effects. To be able to systematically correct for such a bias the sample of pulsars was restricted to those which, in principle, should have been detected by any one of the major eight surveys. The next step is to construct the true galactic distribution of pulsars from the observed distribution. Once again this involves the computation of scale factors. While deriving the current of pulsars we calculated the scale factor as a function of P and $\dot{P}$. In the present context one wants to ask a slightly different question, viz., given any location in the Galaxy where a pulsar has in fact been detected one wants to calculate the *probability* of detecting a pulsar at that location were it to have a different period or different magnetic field. This will enable one to calculate the scale factor as a function of position in the Galaxy. The procedure adopted was the following. In Fig. 5 we have shown the *true* number distribution of pulsars in the B-P plane. This distribution is derived from the observed B-P distribution by computing the scale factor in various "(B, P) bins" as described in Section 2. *The true distribution so derived is equivalent to a probability distribution for the occurrence of the observed periods and magnetic fields.* Thus, given a particular location in the Galaxy and given this probability distribution one can calculate the detection probability or the fraction of pulsars that are likely to be discovered at that particular location. From this one can derive the scale factors and the true galactic distribution of pulsars (Ramachandran and Deshpande, 1994).

As mentioned earlier there is a relative azimuthal angular motion between the spiral pattern and the matter in the Galaxy. Assuming a flat rotation curve for the Galaxy the relative angular rotation is given by

$$\beta(t, R) = V_{rot} \left(\frac{1}{R} - \frac{1}{R_c} \right) t \tag{3}$$

where V_{rot} is taken to be 225 km/s as recommended by the IAU (see Kerr and

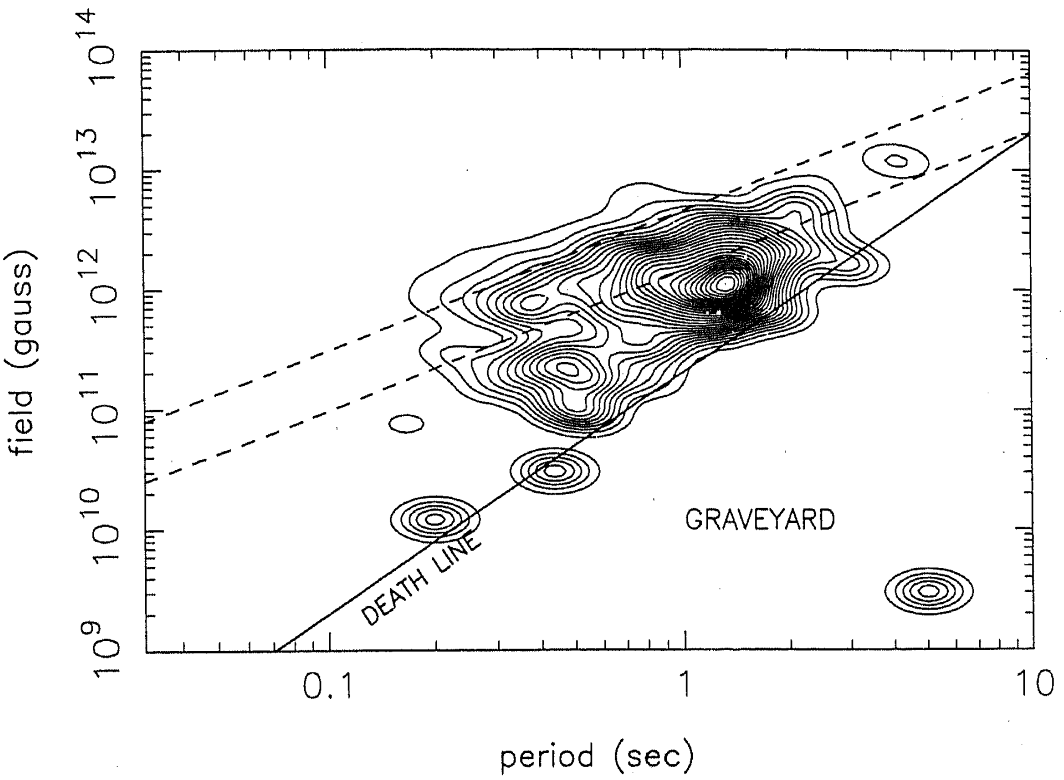

Figure 5: The *true* number distribution of pulsars. The contours have been smoothed with a function shown in the bottom right hand corner of the panel. It may be seen that pulsars in the field range $\log B = 10.5 - 11.5$ appear to form a distinct island; there appears to be a *valley* between the distribution of these pulsars and the high field pulsars. As discussed in Section 4, the statistical significance of this valley is 98.37%. The two 'dash' lines are equilibrium period lines; the lower one corresponds to accretion at the Eddington rate, and the upper one to accretion at 10 times the Eddington rate.

Lynden-Bell 1986). Using this relation the pulsar distribution can be "rotated" as it were with respect to the spiral arms as delineated by the electron density distribution, and one can look for a correlation between the two at some past epoch. The expected correlation (Blaauw, 1985) can, in principle, be smeared due to three effects: (1) the spread in the birth places of the progenitors, (2) the motion of the progenitors between their birth and death, and (3) motion of the pulsars after their birth. The first two effects may not be significant, but the smearing due to the space velocities of the pulsars acquired at their birth could be important. If one finds a correlation despite this then one can turn it around to set limits on the space velocities of pulsars.

Before giving the results of the analysis it is worth recalling two assumptions that have been made in this analysis: (1) the "arm component" of the electron density in the Taylor-Cordes model adequately describes the mass distribution in the spiral structure. This is a reasonable assumption since the electron density model is based on the observations of giant HII regions. (2) In order to define the circular velocity of the spiral pattern a value of 14 kpc has been assumed for the co-rotation radius. As mentioned before, this value is consistent with the detailed modelling of neutral hydrogen in the Galaxy.

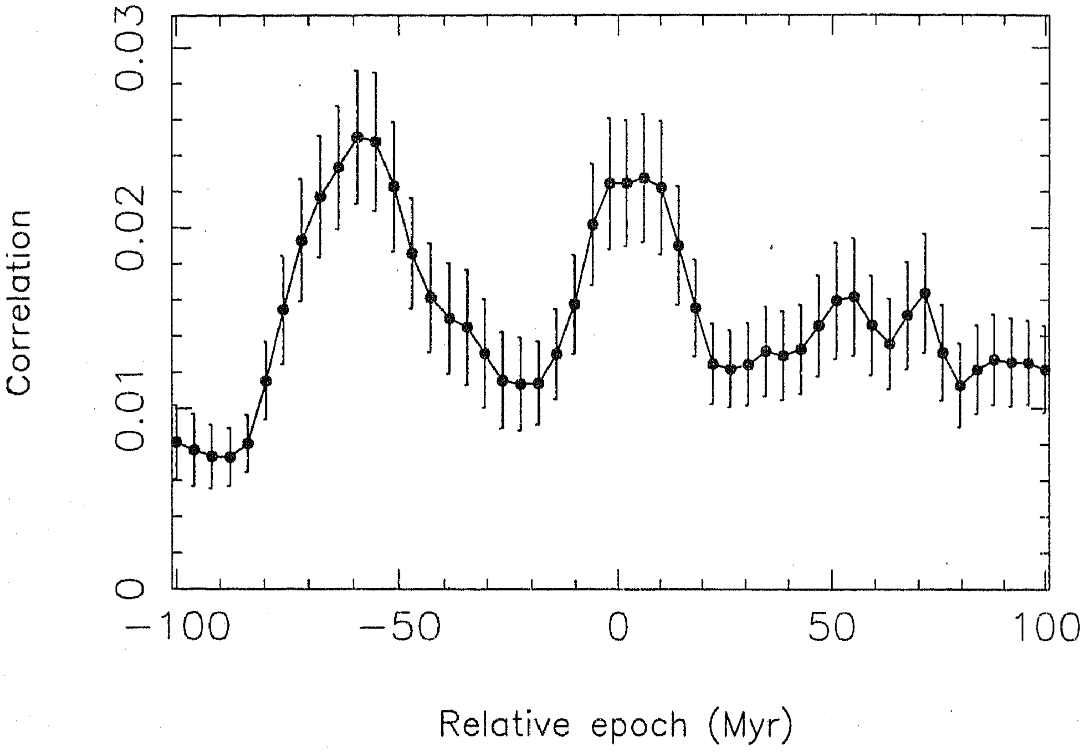

Figure 6: A plot of the correlation between the mass distribution in the spiral arms and the present pulsar distribution as a function of different past epochs. A co-rotation radius of 14 kpc has been assumed in this analysis. The error bars indicate 1σ deviation on either side. There are two strong features in this plot. It is argued in the text that the picture corresponding to the present epoch is most likely an artefact. The feature at −60 Myr has a very high statistical significance of 99.95%.

The conclusion arrived at by Ramachandran and Deshpande (1994) is shown in Fig. 6. Surprisingly there are two significant features, one corresponding to 60 Myr ago and the other to the present epoch. The correlation feature at the present epoch, viz., the correlation between the distribution of pulsars and the *present* spiral structure is most likely an artefact of the apparent clustering of pulsars in the "arm regions". This can happen, for example, if the spiral arm component of the electron density distribution is over-estimated relative to the smooth component. This can also happen if the location of the spiral arms in the model is in error. In the former case one would expect the effect to be more pronounced in the inner Galaxy. This is indeed the case. Pulsars which contribute the correlation at the present epoch are mostly between 5 to 7 kpc from the galactic centre.

Let us now turn to the other feature in Fig. 6 namely the one which corresponds to a correlation between the pulsar distribution and the spiral arms some 60 Myr ago. The following tests were done to test the significance of this feature. The longitudes of the pulsars were scrambled and the whole analysis was repeated. Similarly, the distances to the pulsars were varied randomly by about 30% and the analysis was repeated. Based on many tens of thousands of simulations it was concluded that the correlation maximum at −60 Myr has a significance level of 99.95%. This should be compared with a significance level of about 93% for the other feature, which supports our earlier conjecture that it must be an artefact.

In our opinion the above analysis lends strong support to the prescient remarks of Blaauw that "pulsars are, on a galactic scale, tracers of regions of past spiral structure rather than of active spiral structure". Since the average lifetime of the pulsars in the sample is 10 ± 2 Myr, the above analysis leads one to the conclusion that the average lifetime of the progenitors of the pulsars must be about 50 Myr. This is roughly the lifetime of stars with masses $\sim 7M_\odot$. This would suggest that a pulsar birth rate of 1 in 80 years derived earlier might be an under-estimate. The strong correlation found between the present distribution of pulsars and the location of spiral arms in the past argues against pulsars being high velocity objects. We feel that it may be hasty to conclude that the majority of pulsars are very high velocity objects.

4. On the fraction of pulsars from binary systems

We now turn to a completely different question. So far we have not been worried about whether the progenitors of pulsars are solitary stars or members of binary systems. This is obviously a very important question. Although the number of binary pulsars is still only a couple of dozen there is no reason to conclude that the vast majority of solitary pulsars may not have come from binaries. After all one expects the majority of binaries to disrupt at the time of the second supernova explosion. It would be of great interest if one could estimate the fraction of solitary pulsars which have come from binaries. It may be recalled that the Hulse-Taylor pulsar which is now understood in terms of it being born and recycled in the binary system has an anomalous combination of short rotation period and low magnetic field. If the magnetic field of the first-born pulsar had decayed significantly before being spun up then it will be spun up to relatively short periods and will stand out from the general population of solitary pulsars. On the other hand, if the magnetic field of the first-born pulsar had not decayed significantly then after being spun up it will be deposited inside the island of pulsars close to the spin-up line. Radhakrishnan and Srinivasan (1981) who were the first to address this question tentatively identified PSR 1541−52 and 1804−08 as recycled pulsars from binaries which were disrupted during the second supernova explosion (see Fig. 7).

Why should the magnetic fields of some first-born neutron stars decay more than in others? Although this question will be reviewed later by Bhattacharya (this volume) it is necessary for us to make a few remarks to motivate the discussion that follows. It now appears that the magnetic fields of solitary neutron stars do not decay significantly during their lifetime as pulsars. But there are strong reasons to believe that the magnetic fields of neutron stars born and processed in binary systems do decay. In the model due to Srinivasan et al. (1990) the decay

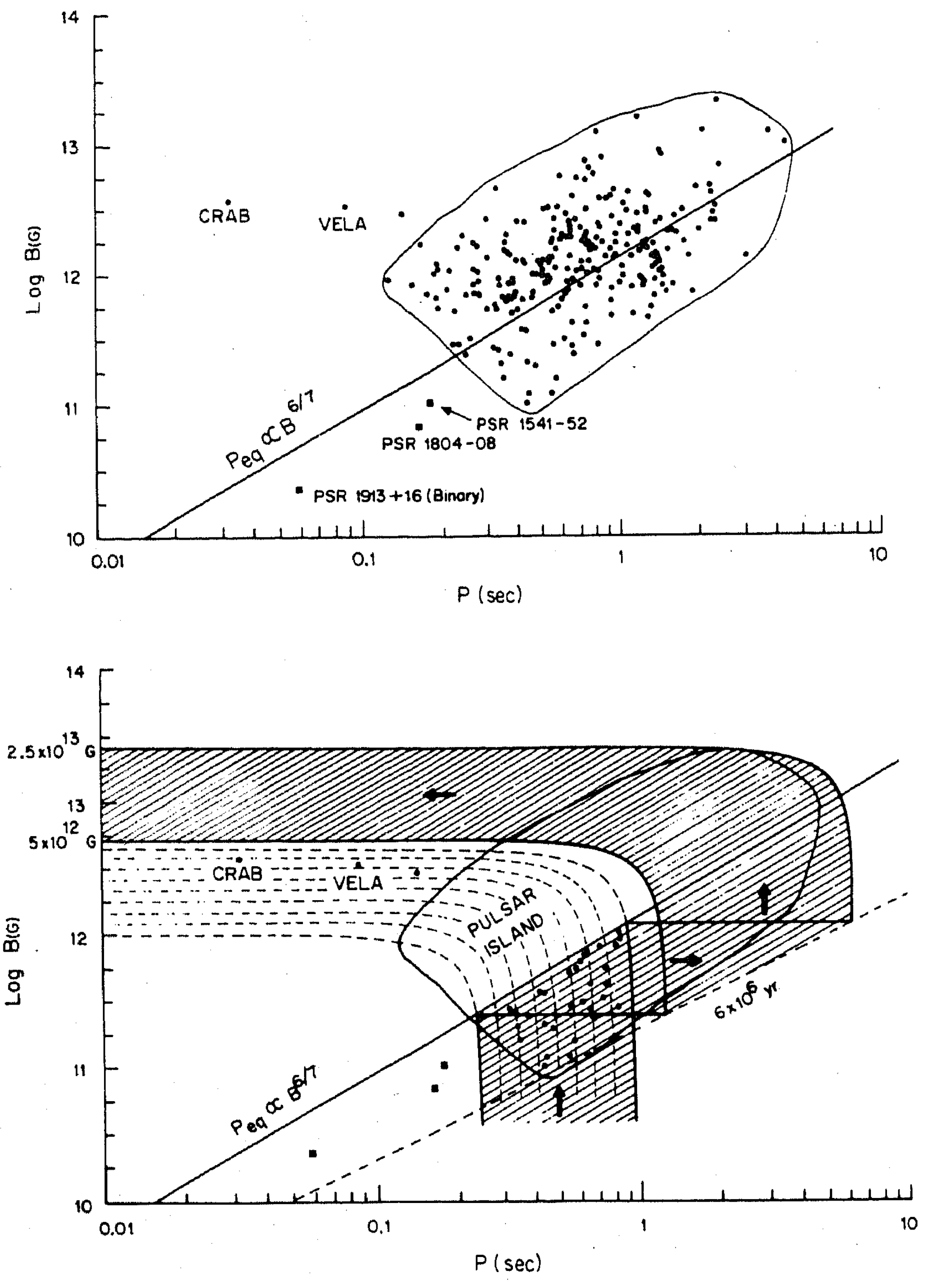

Figure 7: (from Radhakrishnan and Srinivasan, 1981) (a) This shows the population of solitary pulsars which form a distinct island. The binary pulsar PSR 1913+16 is believed to be the first-born pulsar in the binary whose field had decayed between its birth and the onset of mass accretion during which it was spun up to an *equilibrium period* determined by its magnetic field. PSR 1804−08 and PSR 1541−52 were tentatively identified as *recycled pulsars.* (b) It is conceivable that a fraction of solitary pulsars in the main population are such recycled pulsars. They are expected to be located to the *right* of the equilibrium period line. Two possible evolutionary scenarios are shown for the low field pulsars located in the bottom right hand corner of the island: The dashed lines show evolutionary tracks with rapid field decay, and the hatched track shows their evolution (traced backwards) in the recycling scenario.

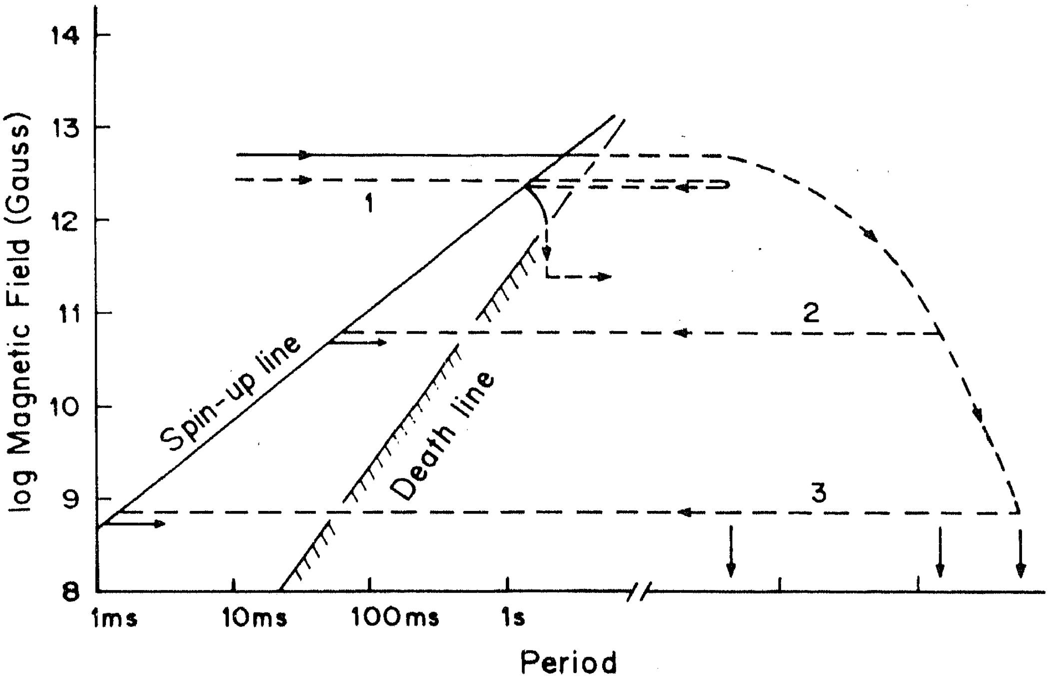

Figure 8: (from Srinivasan et al. 1990) Three possible evolutionary scenarios for recycled pulsars are shown here. Track 3 corresponds to the life history of the first-born neutron star in low mass binary systems. In such systems the magnetic field of the neutron star presumably decays by many orders of magnitude and is spun up during accretion to a period of a few milliseconds. Track 2 represents the life history of recycled pulsars such as PSR 1913 + 16 and PSR 0655 + 44. The progenitors of such pulsars are thought to be intermediate mass binaries, and the decay of the magnetic field of the first-born neutron star is still quite significant. In massive binary systems the first-born neutron star may not be spun *down* significantly enough for a substantial fraction of the core field to be expelled. Consequently the magnetic fields of such pulsars will still be close to its original value when it is spun up during the mass transfer phase. These pulsars will consequently be injected into the normal population of high field solitary pulsars. This scenario is labelled as Track 1. The "spin-up line" in this figure is the equilibrium period line corresponding to accretion at the Eddington rate.

is related to the expulsion of flux from the interior as the neutron star is dramatically spun down during the main sequence phase of the companion. If one accepts this scenario, then there are three possibilities as shown in Fig. 8. In the case of low mass binaries which are presumably the progenitors of millisecond pulsars the neutron stars are possibly spun down sufficiently and over a long time for the field to decay to very low values ($\sim 10^8$ G). In intermediate mass and/or wide binaries, the spin-down and the consequent flux expulsion may be less pronounced as shown in the alternative (2) in the figure. In the case of massive and tight binaries the companion may evolve so quickly that there may not have been time for the flux to decay, even if it had been expelled from the interior to the crust. This is scenario (1) in the figure. Keeping in mind these various possibilities we looked for "injection" of pulsars close to the spin-up line inside the pulsar island. To illustrate our conclusions we will return to our earlier discussion of the pulsar current and the number distribution.

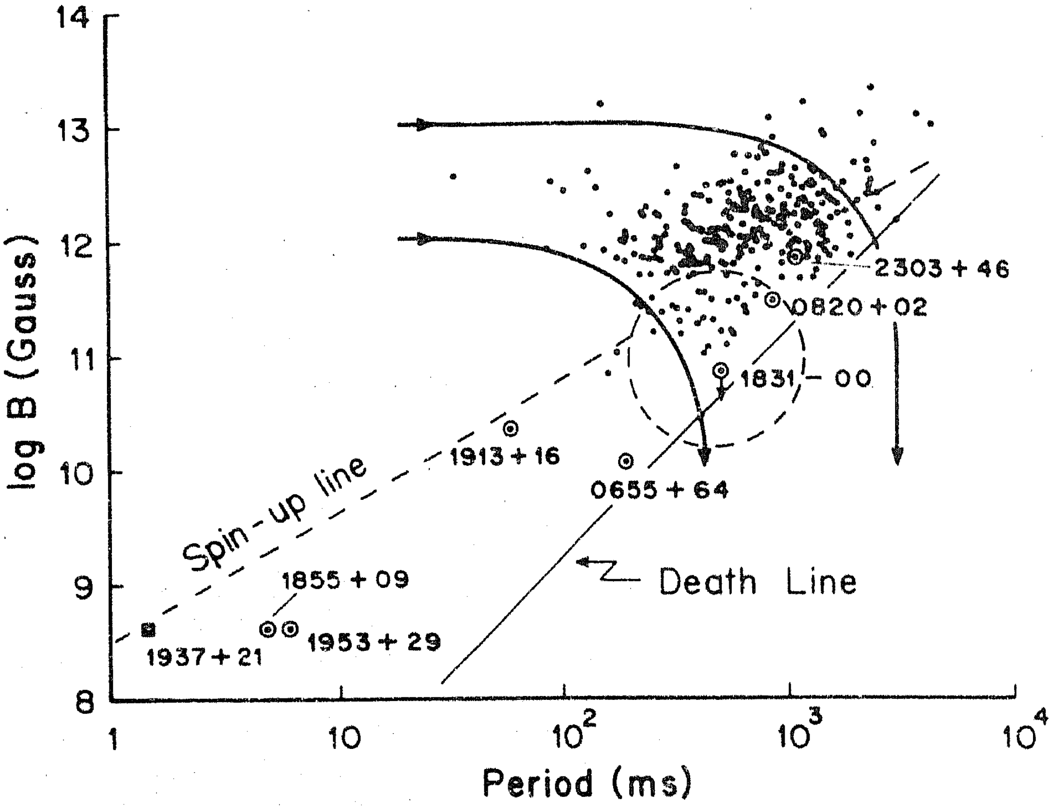

Figure 9: (from Srinivasan 1991) The distribution of observed pulsars. As argued in the text, it is quite likely that the low field pulsars inside the *dashed circle* did not evolve from the left of the diagram due to rapid field decay (as was suspected earlier), but were "injected" close to the spin-up line. In other words, these are most likely *recycled pulsars*.

Let us first concentrate on the encircled pulsars in Fig. 9 with fields less than $10^{11.5}$ G. Let us ask how these pulsars would have evolved to their present position in the diagram. They could have evolved from the left. In this scenario there are two possibilities. If one entertains field decay with relatively short timescales, then their evolutionary track would be the curved line in the figure. Indeed one should say this in exactly the opposite manner! It is this argument that led to a field decay timescale of 3 – 4 Myr that was popular a few years ago. Such a short decay timescale is definitely not preferred now.

This leaves open the possibility that these pulsars evolved horizontally from the left. If this is the case one would expect to see at least a few pulsars with similar fields but shorter periods. Since such pulsars would have higher luminosities by virtue of their higher periods their absence cannot be easily attributed to selection

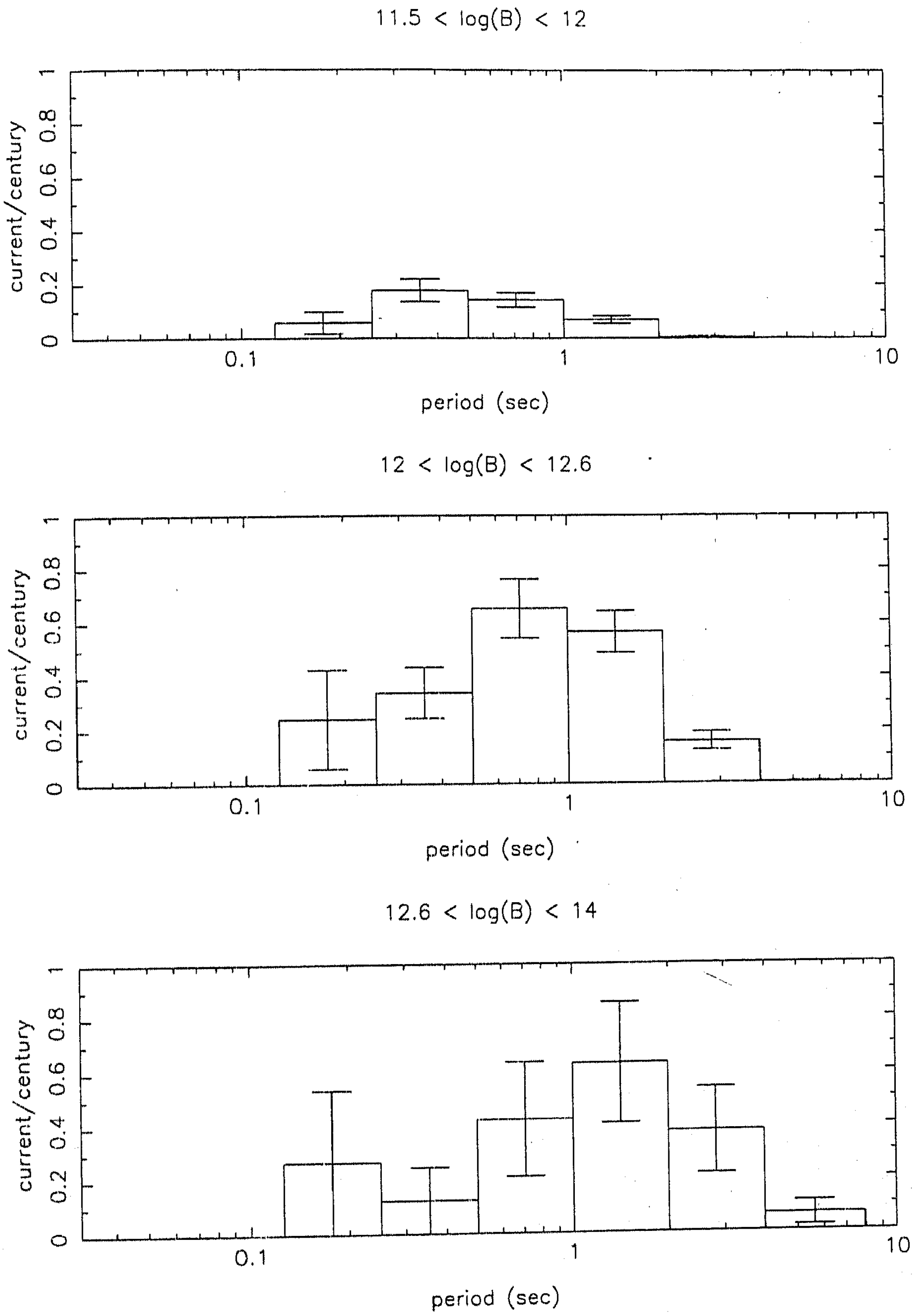

Figure 10: The current distribution shown in Fig. 2 has been binned into three magnetic field ranges. As may be seen, it is only in the central panel which corresponds to $12 < \log B < 12.6$ that one sees a *step* in the current at a period of about 0.5 s.

effects. But this could easily be due to their low birth rate. That their birth rate is low can be easily deduced from their contribution to the *current*. Pulsars in this field range are born once in about 5000 years. Thus one cannot rule out the possibility that these low field solitary pulsars evolved from the left. But there is an argument which suggests that this might not have been the case. Let us return to the true number distribution of pulsars shown in Fig. 5. To recall, this distribution is obtained from the observed distribution by allowing for various selection effects. It may be seen in the figure that the low field pulsars that we have been discussing seem to form a distinct island. In other words, there appears to be a 'valley' between the population of high field and low field pulsars. To test the statistical significance of this valley we performed some simulations by scrambling the periods and magnetic fields of the pulsars in the distribution. (To be more precise, the $\dot{P}$s were scrambled keeping the luminosity distribution unchanged.) From a large number of simulations we find that the valley in the number distribution of pulsars has a significance level 98.37%.

If one takes this seriously then one has to either invoke a bimodal distribution of magnetic fields at birth, or conclude that the low field pulsars possibly evolved to their present position from the *right* in the diagram. In other words, they might be recycled pulsars from binary systems.

Let us now move to the upper island of pulsars in Fig. 5 and ask whether there is any sign of injection of pulsars close to the spin-up line. A signature of such an injection of recycled pulsars into the island of solitary pulsars would be a *step* in the current close to the spin-up line. The integrated current of pulsars over the entire field range shown in Fig. 2 suggests a step in the current at a period around 0.5 s. In Fig. 10 we have once again shown the current distribution but this time binned into different field ranges. As may be seen, a step in the current is seen only in the field range $10^{12} - 10^{12.6}$ G. Admittedly the formal statistical significance of this feature is not very high. But the fact that there is a correlation between the period at which such an injection occurs and the magnetic fields of the injected pulsars suggests that one might take this seriously. Given this correlation between the rotation periods and magnetic fields one is led to the conclusion that this injection may be associated with recycled pulsars making their appearance close to the spin-up line. Narayan and Ostriker (1990) also found such a feature in their detailed statistical analysis (which was not based upon the current of pulsars).

The correlation between the rotation periods and the magnetic fields of the injected population may be seen better in Fig. 11. where we have plotted the current as a contour diagram in the B-P plane. This current is calculated using eqn. 1 in various magnetic field "bins". Concentrating for a moment in the field range $10^{12} < B < 3 \times 10^{12}$ G, one can see that the current builds up rather continuously till a period of about 0.5 s, at which there is a step or a cliff. (As may be readily seen, the contour plot reveals many "hills". These are merely individual high $\dot{P}$ pulsars which appear as "little hills" due to the fact that the current distribution has been smoothed with the function shown in the right hand bottom corner of the plot. Contrary to this, the step in the current referred to above, and also discussed in the above paragraph, is a statistically significant feature since a fairly large number of pulsars contribute to it.) Also shown in the figure are two equilibrium period lines corresponding to the Eddington accretion

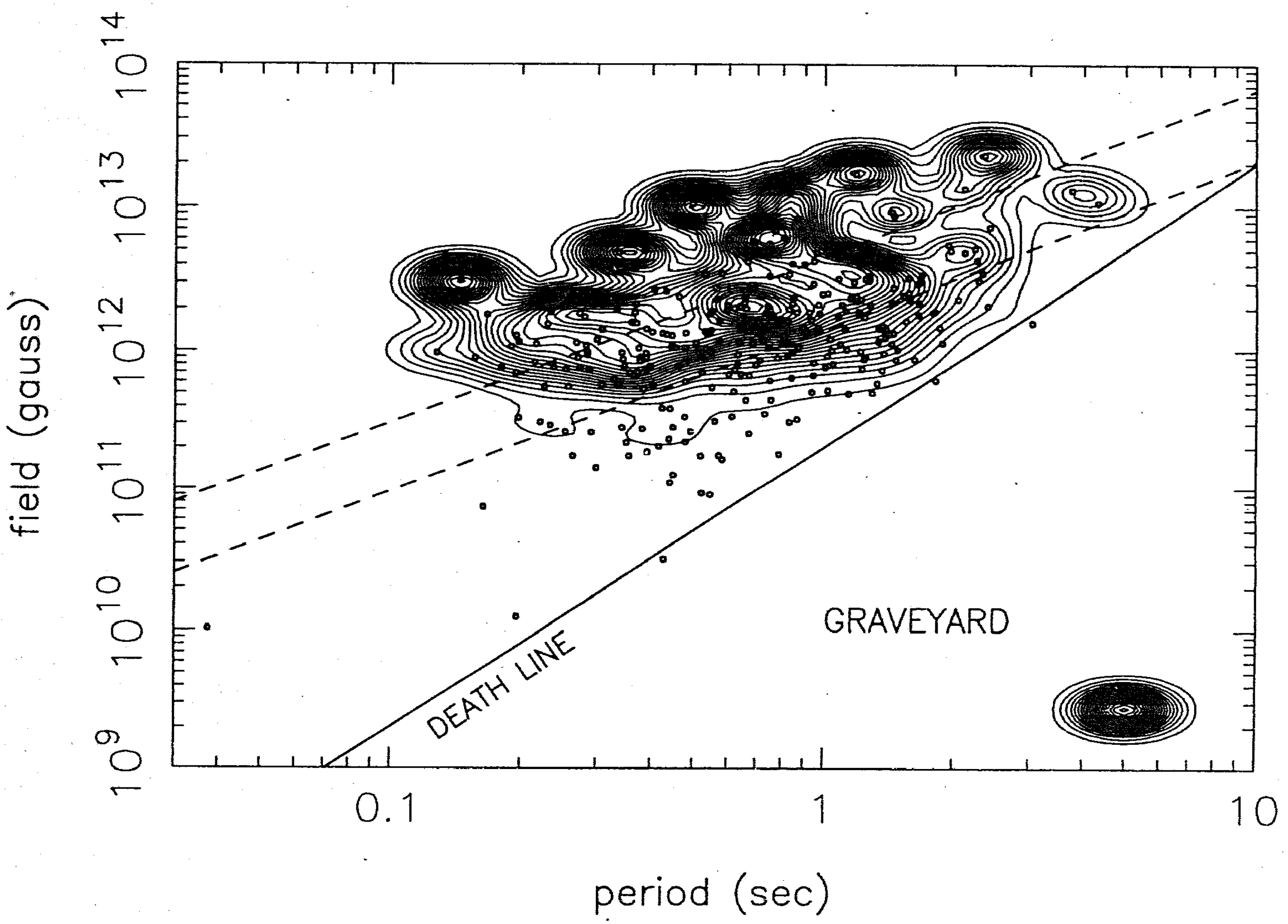

Figure 11: This shows the current distribution as a function of the period and magnetic field. This distribution has been smoothed with a function shown in the bottom right hand corner of the panel. Most of the "hills" seen in this distribution corresponds to individual high $\dot{P}$ pulsars. But the distinct "cliff" in the field range $10^{12} < B < 3 \times 10^{12}$ G and a period around 0.5 s is a statistically significant feature since a fairly large number of pulsars contribute to it. It is this step in the current close to the upper spin-up line ($\dot{M} = 10\dot{M}_{Edd}$) that we interpret an injection of recycled pulsars from massive binaries.

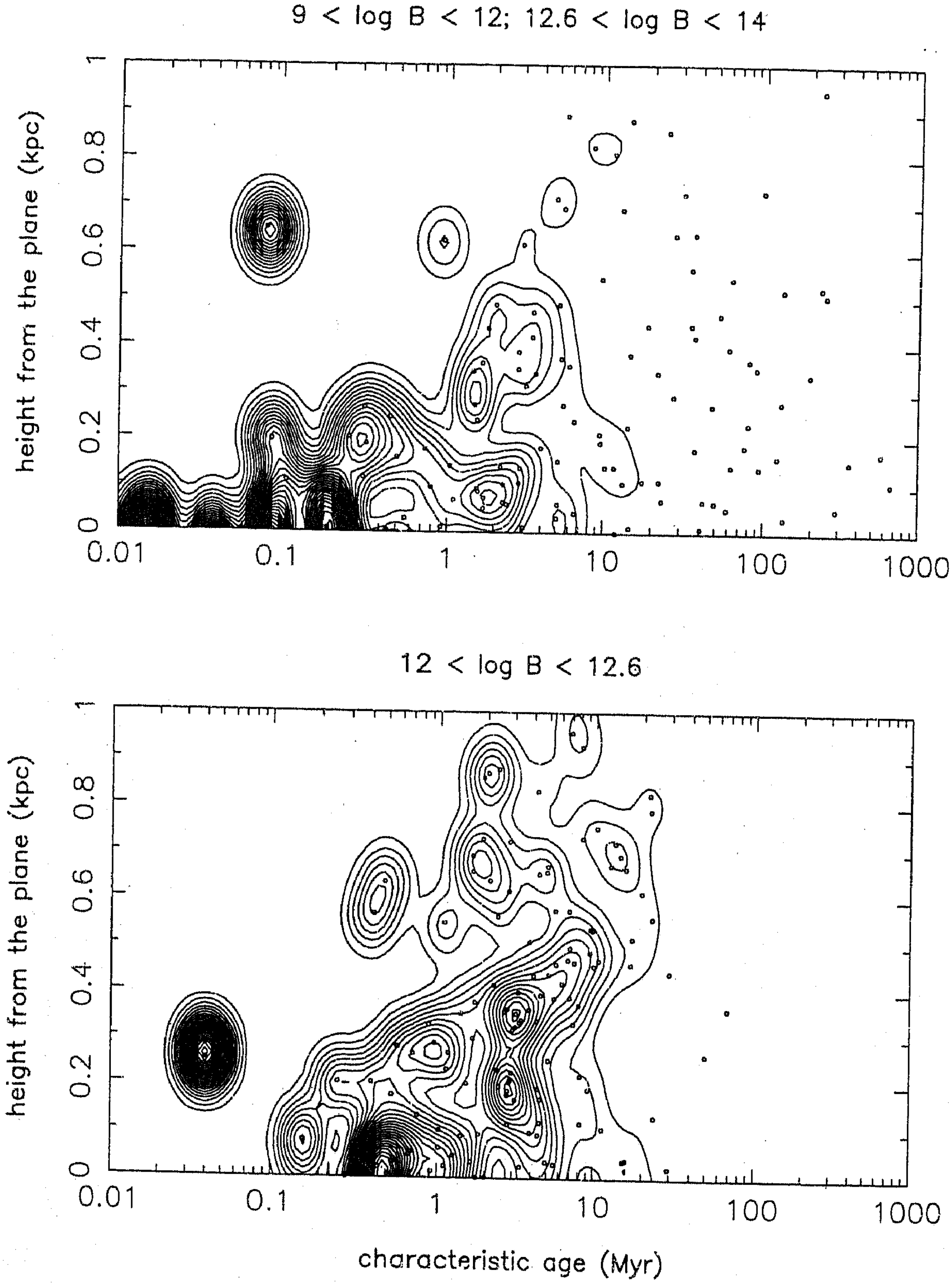

Figure 12: The pulsar current as a function of the characteristic age and the height z from the galactic plane. (a) In this panel we have deliberately *excluded* pulsars in the field range $12 < \log B < 12.6$ in which we believe there may be a substantial fraction of recycled pulsars. The distribution shown is easily understood in terms of the majority of pulsars being born close to the galactic plane and migrating away from it due to velocities acquired at birth. (b) In this figure the current of pulsars in the magnetic field range $12 < \log B < 12.6$ alone is shown. We wish to suggest that this distribution is more consistent with pulsars not only being injected with a characterstic age of about 1 Myr but at a variety of distances from the galactic plane ranging all the way up to 800 pc.

rate and ten times its value. Therefore, if the injection is interpreted as due to recycled pulsars it would imply that they experienced accretion at a super-Eddington rate. In our opinion this is quite likely to happen in massive binary systems.

Further support for our conjecture that the injection of pulsars (at a period around 0.5 s and with magnetic fields in the range $12 < \log B < 12.6$) may be related to recycled pulsars comes from the distribution of these pulsars with respect to the galactic plane. Fig. 12 shows the pulsar current as a function of the characteristic age and the distance z from the galactic plane; the pulsars in the sample are shown as open circles. To bring out the point that something special may be happening in the field range mentioned above, we have shown the current distribution in two separate field ranges. In Fig. 12(a) we have *excluded* the field range $12 < \log B < 12.6$, and in Fig. 12(b) we have shown *only* those pulsars which have magnetic fields in this narrow range. Fig. 12(a) is consistent with majority of pulsars being born with relatively short periods and within a hundred parsec or so from the galactic plane, and their subsequent migration from the plane due to velocities acquired at birth. On the other hand, Fig. 12(b) looks very different. In our opinion this is more consistent with an injection of pulsars with characteristic ages of about 1 Myr and injected at a variety of distances from the galactic plane.

What could be the progenitors of these pulsars which explode at substantial distances from the galactic plane? It is conceivable that a certain fraction of binaries acquire substantial centre of mass velocities during the first explosion, and a certain fraction of them migrate *away* from the galactic plane. When such binaries disrupt during the second supernova explosion two pulsars will be released. The first-born will have the characterstics of a recycled pulsar, and the second one will have a short characterstic age at birth. In our opinion this offers a natural explanation for why some short characterstic age pulsars are seen to be moving *towards* the galactic plane (Harrison et al. 1993).

5. Summary

We wish to briefly summarize the main conclusions presented in this paper:

1. Our analysis of the current of pulsars yields a birth rate of 1 in 80 years.
2. There appears to be a strong correlation between the present distribution of pulsars and the location of the spiral arms of the Galaxy some 60 Myr ago.
3. If this correlation is confirmed by future analyses using a larger population of pulsars then it would lead one to conclude that the majority of progenitors of pulsars must be relatively low mass field stars ($M \sim 7 - 10 M_{\odot}$) thus confirming the remarkable conjecture by Blaauw (1985).
4. Our analysis indicates that the population of solitary pulsars may include a certain fraction of recycled pulsars which were released from binaries that were disrupted during the second supernova explosion. Tentatively we would like to suggest that about 10% to 15% of solitary pulsars might have been processed in binary systems.

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