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On Selection Effects in Pulsar Searches

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Abstract. Selection effects are a major source of error in statistical studies of pulsar data since the observed sample is a biased subset of the full galactic pulsar population. It is important to identify all selection effects and make a reasonable model before attempting to determine pulsar properties. Here we discuss a hitherto neglected selection effect which is a function of the period P of the pulsar. We find that short-P pulsars are more difficult to detect, particularly if their dispersion measures are high. We also discuss a declination-dependent selection effect in the II Molonglo Survey (II MS), and find some evidence for the existence of both selection effects in the pulsar data from this survey. We discuss the implications of these additional selection effects for the recently proposed 'injection' of pulsars whereby pulsars seem to switch on only at longer P. Using the II MS data we calculate that the observability of pulsars with P between 0·0 s and 0·5 s is about 18 per cent less with the new selection effects than hitherto believed; the mean correction is 6 per cent for P between 0·5 s and 1·0 s. We conclude that injection is not qualitatively affected by these corrections.

Key words: pulsar searches—selection effects

1. Introduction

Vivekanand and Narayan (1981; henceforth VN) have shown that there is apparently a physical deficit of pulsars with periods $P < 0{\cdot}5$ s. Before seeking an explanation for this so-called 'injection' of pulsars at long periods, it is important to verify that it is a genuine pulsar phenomenon and not an artifact arising from some period-dependent selection effect in pulsar searches.

It is currently believed that a satisfactory representation of the minimum detectable flux $S_{\min}$ of a pulsar survey is that given by Taylor and Manchester (1977)

$$S_{\min} = S_0\, \beta\, (1 + T_{\mathrm{sky}}/T_{\mathrm{r}})\; (1 + D/D_0)^{1/2}\ \mathrm{mJy} \tag{1}$$

where T_{sky} and T_r are the sky and receiver noise temperatures, D is the dispersion measure of the pulsar, D_0 is a constant, S_0 is the minimum sensitivity of the survey and β is a factor (greater than 1) representing the reduction in sensitivity resulting from displacement of the source from the beam centre. In Equation (1), S_{min} does not depend upon P; indeed, Taylor and Manchester (1977) only refer to a limiting period (of the order of tens of milli-seconds) above which the sensitivity of the survey is believed to be uniform, and below which the sensitivity decreases rapidly. However, much earlier, Large and Vaughan (1971) had demonstrated the presence of a selection effect, dependent both on P and D, in the I Molonglo Survey (I MS). Because the I MS used a different method for pulsar search than that currently employed, their results are not directly relevant today.

In this paper we argue that two modifications to Equation (1) are necessary. Firstly, S_{min} depends not on the dispersion measure D alone (as in Equation 1) but on D/P (this is related to the effect discussed by Large and Vaughan 1971). Hence, short period pulsars are more difficult to detect than Equation (1) would suggest. Huguenin (1976) has mentioned the period-dependent selection effect and has pointed out that short-period, high-dispersion pulsars are very difficult to observe. This could have implications when analysing period-dependent effects such as injection. Secondly, high-declination (δ) pulsars are somewhat easier to detect because some surveys (*e.g.* II Molonglo Survey, hereafter II MS; Manchester *et al.* 1978) spend longer observing times at higher δ. Since δ is correlated with height above the galactic plane (z), particularly for nearby pulsars, this could have consequences for z-dependent studies of pulsars. Equation (6) gives a new formula for S_{min} incorporating these new effects.

Table 1 shows that both the above effects are indeed present in the II MS. Table 1(a) considers the II MS pulsars in three period bins. In each bin we have tabulated (i) the number of pulsars (n_0) detected below the quoted minimum detectable flux, *i.e.* pulsars with $S_{pulsar}/S_{min} < 1$ where S_{min} is given by Equation (1), (ii) the total number of pulsars detected ($n_0 + m_0$), (iii) the expected number of pulsars (n_e) with $S_{pulsar}/S_{min} < 1$, based on the total n_0 in all the bins, $n_e = (n_0+m_0)(\sum n_0)/(\sum n_0 + \sum m_0)$, *i.e.* $n_e \propto (n_0 + m_0)$, (iv) the difference $n_0 - n_e$ and (v) the expected standard deviation (σ) on ($n_0 - n_e$). It is reasonable to expect that n_0 should differ from n_e in each bin by a quantity of the order of σ. Table 1 (a) shows that this is clearly not so. We obtain a χ^2 (computed as $\sum \{(n_0 - n_e)^2/\sigma^2\}$;

Table 1. Each column shows (i) observed number of pulsars (n_0) with $S_{pulsar}/S_{min} < 1{\cdot}0$, (ii) all pulsars in that bin ($n_0 + m_0$), (iii) expected number (n_e) with $S < S_{min}$ in the bin, (iv) the difference ($n_0 - n_e$), and (v) standard deviation (σ) on $n_0 - n_e$. S_{min} was derived using Equation (1).

	(a) Pulsars in bins of period (in seconds):			(b) Pulsars in bins of declination:		
	$0{\cdot}0 \leqslant P < 0{\cdot}5$	$0{\cdot}5 \leqslant P < 1{\cdot}0$	$1{\cdot}0 \leqslant P < 1{\cdot}5$	$0° \leqslant \delta < 30°$	$30° \leqslant \delta < 60°$	$60° \leqslant \delta < 90°$
n_0	11	21	19	18	26	16
$n_0 + m_0$	76	89	40	97	89	38
n_e	18·9	22·1	10·0	26	23·8	10·2
$n_0 - n_e$	−7·9	−1·1	9·0	−8·0	2·2	5·8
σ	3·0	2·9	2·45	3·3	3·24	2·5

see Section 3 for details) of 20·6 against the expected value 3·0, implying that S_{min} probably has some P-dependence in addition to the factors written down in Equation (1). In Table 1 (b), which considers the declination dependence, we similarly obtain a χ^2 of 11·8 against 3. These results appear to suggest that Equation (1) may not be an adequate description of the selection effects in pulsar surveys.

In Section 2 we present the theory of the new selection effects. Our results for the dependence of S_{min} on D/P differ quantitatively from those of Large and Vaughan (1971); we offer a possible explanation for this. In Section 3 we present some evidence to show that our modified formula for S_{min}, which for practical purposes can be simplified to Equation (8), is a better representation of the selection effects in the II MS than Equation (1). In particular, it is shown that arguments similar to those used in Table 1 but with the new S_{min} (Equation 8) give results significantly more consistent with the observations. We demonstrate in Section 4 that these extra selection effects we have discussed are unimportant as far as the recently derived pulsar injection properties are concerned. There continues to be strong evidence for the sudden appearance of many pulsars at long periods. Another possible selection effect due to the period derivative $\dot{P}$, which might have a P dependence, is briefly discussed. It is conlcuded that this is not likely to be of importance.

2. Theory of the selection effects

In Fig. 1, we have schematically plotted the signal as a function of time in the de-dispersed folded output from a pulsar survey. The plot is for the duration of one period, and signal strength is measured in units of temperature. Due to the ionized interstellar medium, the intrinsic pulse width w is broadened to $w+t$, where t is the dispersion broadening in a single frequency channel. In what follows we assume that (a) the signal is folded at the correct P of the pulsar, (b) the time resolution of the

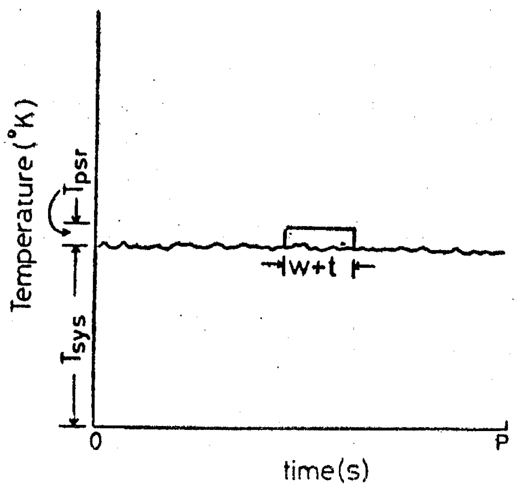

Figure 1. A schematic folded output from a pulsar survey. T_{sys} is the system noise level, and T_{psr} is the mean pulsar level for the pulse duration. The pulse of intrinsic width w is broadened by t because of dispersion in the interstellar medium. For convenience in presentation the fluctuations in T_{sys} have been scaled down.

data is $1/B$ where B is the bandwidth, (c) the signals in the various channels have been de-dispersed with the correct delay, and (d) the position of the pulse and its width $(w+t)$ have been properly identified in the integrated profile. We later show that (b) is not a necessary requirement.

Let the mean system temperature without the pulsar be T_{sys}. This is the receiver temperature T_{r} plus the background sky contribution; so

$$T_{\text{sys}} = T_{\text{r}}\,(1 + T_{\text{sky}}/T_{\text{r}}). \tag{2}$$

Let the pulsar under consideration, with mean signal strength T_{psr} within the pulse window, be just at the threshold of detectability. For detection, the difference between the mean level $(T_{\text{psr}} + T_{\text{sys}})$ *on-pulse* and the mean level T_{sys} *off-pulse* should be some factor n (typically 5) times the noise σ_{diff} on the difference. Now

$$\begin{aligned}\sigma_{\text{diff}} &= (\sigma^2_{\text{on}} + \sigma^2_{\text{off}})^{\frac{1}{2}}\\ &= \left\{\frac{T^2_{\text{sys}}}{(\tau/P)\,(w+t)\,B} + \frac{T^2_{\text{sys}}}{(\tau/P)\,(P-w-t)\,B}\right\}^{\frac{1}{2}}\end{aligned} \tag{3}$$

where τ is the total observation time per sky position. Hence at the threshold of detection

$$T_{\text{psr}} = \frac{n\,T_{\text{r}}}{(\tau\,B)^{\frac{1}{2}}}(1 + T_{\text{sky}}/T_{\text{r}})\left[\frac{1}{(w+t)/P}\right]^{\frac{1}{2}}\left[1 + \frac{w+t}{P-w-t}\right]^{\frac{1}{2}}. \tag{4}$$

T_{psr} can be written in terms of the mean pulsar flux density S (energy per pulse divided by period) as

$$T_{\text{psr}} = \frac{1}{\beta}S\left[\frac{P}{w+t}\right]\frac{A}{k_{\text{B}}} \tag{5}$$

where β has been defined in Equation (1), A is the effective collecting area of the telescope and k_{B} is Boltzmann's constant. Let us use the symbol d for the pulsar duty cycle (w/P), and write the dispersion broadening explicitly as $t = K_1\,D$ where K_1 is a constant proportional to B. Further, the total observation time $\tau = \tau_0/\cos\,\delta$ for transit observations such as II MS, where τ_0 is assumed to be a constant for a given survey. We then obtain

$$S_{\min} = \beta\,S_0\,(1 + T_{\text{sky}}/T_{\text{r}})\,(d/d_0)^{\frac{1}{2}}\left[1 + \frac{K_1\,D}{Pd}\right]^{\frac{1}{2}}\left[1 + \frac{Pd + K_1\,D}{P - Pd - K_1\,D}\right]^{\frac{1}{2}}(\cos\,\delta)^{\frac{1}{2}} \tag{6}$$

where d_0 is a reference value of the duty cycle for all pulsars (taken to be 0·04) and S_0 is defined by

$$S_0 = \frac{n\,T_{\text{r}}\,k_{\text{B}}\,d_0^{\frac{1}{2}}}{A\,(\tau_0\,B)^{\frac{1}{2}}} \tag{7}$$

which is a constant for a given survey (assuming A is independent of δ as is true for the II MS). For convenience, we will refer to the term $(d/d_0)^{\frac{1}{2}}$ as term A, the terms in the first and second square brackets in Equation (6) as terms B and C respectively and the term $(\cos \delta)^{\frac{1}{2}}$ as term D.

In Equation (6) the term C is not prominent until the pulse width $(w+t)$ becomes a significant fraction of P. Since this is rare, except when the effects of multipath propagation become overwhelming, C can usually be taken as 1. The term D essentially represents the increased integration time at higher declinations for surveys such as the II MS*. The term B has a non-trivial period dependence (actually D/P dependence) which we wish to highlight in this paper. In the light of this term, we see that Equation (1) is valid only at one value of period, P_0, which can be obtained by equating $P_0\, d_0/K_1$ in Equation (6) to D_0 in Equation (1). If P_0 turns out to be the average period ($\approx 0{\cdot}7$ s) for pulsars, one might argue that Equation (1) is valid in an average sense. However, the values of P_0 which we obtain for the three major surveys, *viz.* Jodrell Bank Survey, Arecibo Survey and II MS are 3 s, 0·8 s and 1·6 s respectively. We thus conclude that Equation (1) does not properly represent the selection effects at low periods, where significant fractions of the Galaxy might be relatively inaccessible to the surveys. As an illustration, for $P < 0{\cdot}4$ s, the sensitivity of II MS is reduced by more than $\sqrt{2}$ over more than 90 per cent of the volume of the Galaxy. The term A in Equation (6) shows the variation of $S_{\min}$ with duty cycle d. This term is important if $t < w$, when the term B collapses to ≈ 1. If $t \gg w$, the $d^{\frac{1}{2}}$ in A is approximately cancelled by $d^{-\frac{1}{2}}$ in B.

What happens when the pulse width $w+t$ is not resolved in the integrated profile? This occurs for nearly 20 per cent of the pulsars detected by the II MS where the minimum time resolution was not $1/B$ but a much larger quantity $t_0 = 20$ ms. In the case when $w+t<t_0$, $w+t$ is to be replaced by t_0 in both Equations (4) and (5), and Equation (6) implies $S_{\min} \propto P^{-\frac{1}{2}}$. In the intermediate situation when w and t are both $< t_0$ but $w+t > t_0$, Equation (6) continues to be valid. Thus, in all cases, the period dependence of $S_{\min}$ remains and cannot be neglected.

To summarize, we believe that Equation (6) is a better formula to be used in describing selection effects in pulsar searches (such as the II MS). Equation (1) is inadequate particularly at short periods, and is not appropriate for studies such as injection (VN) which seek to determine pulsar properties as a function of period.

We should mention here that Large and Vaughan (1971) experimentally demonstrated the variation of $S_{\min}$ with both P and D for the I MS. We have verified that their $S_{\min}$ (Fig. 4 in their paper) depends approximately upon the specific combination (D/P) as in our formula (term B). To make a more detailed comparison with our theory, we have estimated the function $F = -\,d\,(\log S_{\min})/d\,(\log P)$ from their published curves of $S_{\min}$ for the three systems they have studied, *viz.* single channel, double channel and 20 channel systems (Figs 4, 5 and 6 respectively in their paper). In all cases we find that their results imply values of F greater than 0·5. On the other hand, our formula (Equation 6) shows that F should asymptotically tend to a maximum value of 0·5 at small periods (assuming that P is not so small that term C

*This term would be absent for the Jodrell Bank survey (Davies, Lyne and Seiradakis 1972, 1973) which tracked the search regions and would be more complicated for the Arecibo Survey (Hulse and Taylor 1974, 1975) where the effective area of the telescope is highly zenith-angle dependent.

becomes important). It thus appears that the I MS had a stronger dependence of S_{min} on D/P than we expect from our theory.

The discrepancy between the results of Large and Vaughan and our theory is puzzling, since both refer to the same effect. We feel that it probably arises from the visual pulse-search method used in I MS to detect pulsars from chart records. Considering the complex pattern-recognition powers of the human eye it is quite possible that sensitivity falls off rapidly as the pulses are broadened. Our formula on the other hand refers to a computer search on digitized data, which could have totally different sensitivity characteristics. We show in the next section that the data from the II MS (which used a computer search technique) are in good agreement with our theory.

3. Evidence from pulsar data

We have carried out some simple tests on pulsar observational data to confirm that the new selection effects discussed in the previous section really exist. The calculations have been done on the sample of pulsars detected by the II MS. This is the most recent as well as the most extensive of all the pulsar surveys, and yielded a total of 224 pulsars. In what follows, we assume that all pulsars have the same duty cycle d_0, for the following reasons. Firstly, we feel that duty cycles which are derived from pulse equivalent widths (W_e) may not be appropriate in Equation (6). Some calculations we have done using Equation (6) do indeed suggest that W_e is an unreliable parameter for our purposes here. Secondly, d is found to be almost independent of P; so this approximation will not introduce any *systematic* period-dependent effects into our results. Thirdly, the discussion in the previous section shows that the d-dependence in Equation (6) is likely to be weak in the majority of cases. We therefore replace d by d_0 in Equation (6) to obtain

$$S_{min} = \beta S_0 (1 + T_{sky}/T_r) (1 + K_2 D/P)^{1/2} (\cos \delta)^{1/2} \tag{8}$$

where K_2 $(=K_1/d_0)$ is a constant.

Figs 2 and 3 show the results of some tests we have carried out on the II MS data using the old (Equation 1) and new (Equation 8) formulae for the selection effects. In Fig. 2(a) we have plotted the number of pulsars detected (N_0) against a normalized flux X (derived from Equation 1).

$$X = S/\{\beta (1 + T_{sky}/T_r) (1 + D/D_0)^{1/2}\}. \tag{9}$$

The pulsars have been sorted into bins of width 0·2 in $\log_{10} X$. Fig. 3(a) shows results using a similar definition of X based on Equation (8). In both Figs 2(a) and 3(a) N_0 decreases at high X because the pulsar number density itself decreases at higher luminosities. N_0 also decreases for low values of X (below S_0) because of the reduced sensitivity of the survey. Under ideal conditions, this transition should be quite sharp, around $X = S_0$. However, in actual practice it is broadened. Firstly, there is a statistical broadening caused among other things by the variability of pulsar luminosities (*cf.* Krishnamohan 1981). Secondly any unaccounted selection effect

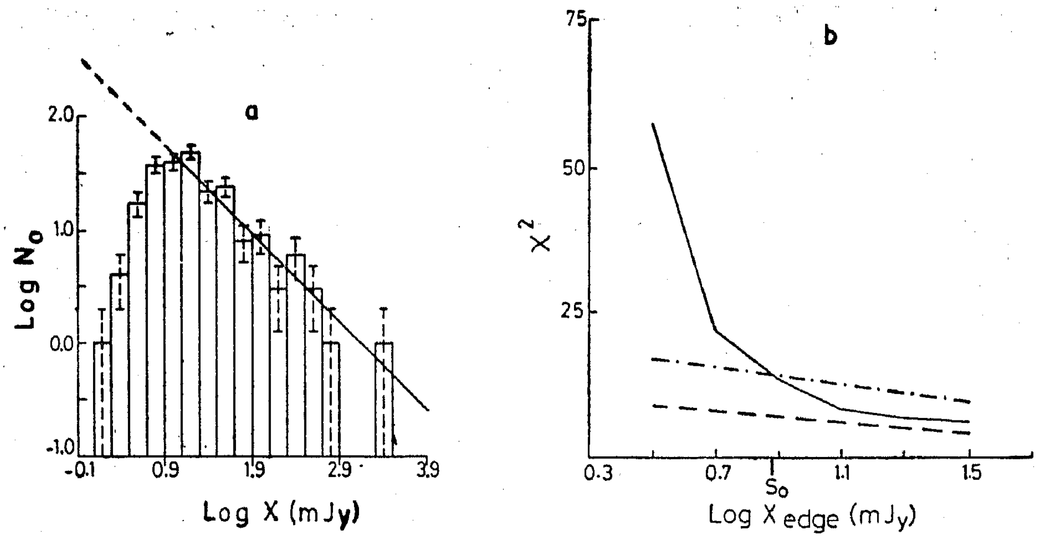

Figure 2. (a) Histogram of observed number of pulsars (N_0) against normalized flux $X = S/\{\beta\,(1 + T_{\mathrm{sky}}/T_{\mathrm{r}})\,(1 + D/D_0)^{1/2}\}$. The error bars represent variance at the level of one standard deviation ($= \sqrt{N_0}$). The solid line is the least-squares fit of a straight line to the data in the descending limb of the histogram and gives the expected number of pulsars (N_{e}). The dashed line is its extrapolation. (b) Plot of χ^2 obtained by fitting the curve $N_{\mathrm{e}} = a\, X^{-\beta}$ to the descending limb in Fig. 2(a) (solid line), along with the expected value (dashed line) and its 95 per cent confidence upper bound (chained line). X_{edge} is the lowest X value used in the curve fitting. The χ^2 increases rather abruptly from its normal value around $X_{\mathrm{edge}} = S_0$, showing that the curve fitting has broken down.

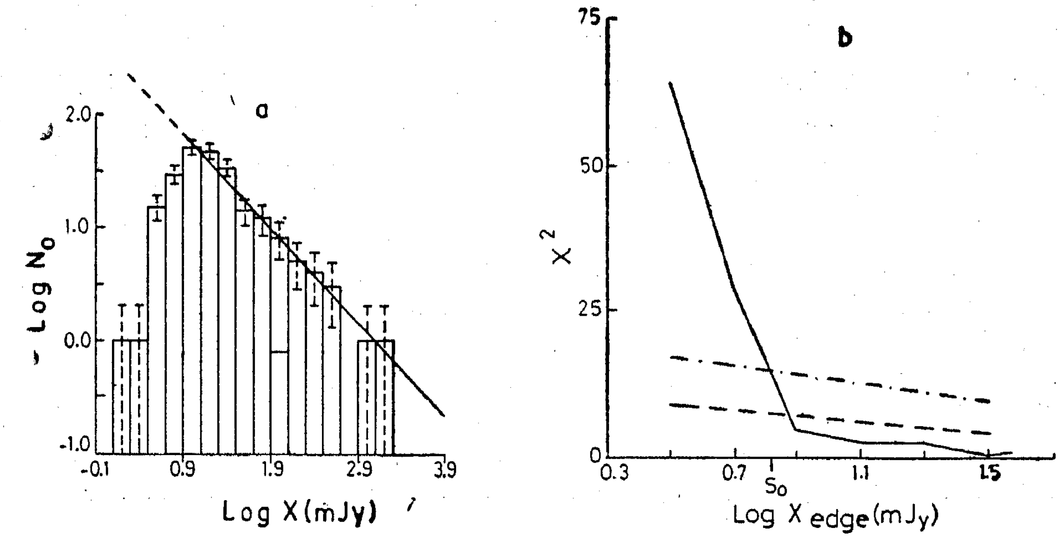

Figure 3. Same as in Fig. 2, with $X = S/\{\beta\,(1 + T_{\mathrm{sky}}/T_{\mathrm{r}})\,(1 + K_2 D/P)^{1/2}\,(\cos\,\delta)^{1/2}\}$.

would broaden the transition. The width of the transition region σ_{tr} can therefore be used to decide which of Equations (1) and (8) fits the II MS data better.

Another test is the number of pulsars below $X = S_0$. As mentioned before, under ideal conditions the transition region is very sharp and there will be no pulsars below S_0. Any selection effect tends to smear out S_0 so that there are now pulsars below it.

To carry out the above tests we had first to determine S_0 for Equations (1) and (8). This was done as follows. Starting with Fig. 2(a), we initially assumed a certain value of X on the descending limb of N_0 *vs* X to be S_0. We took all bins above this value of X (we shall call it X_{edge}) and fitted a curve of the form $N_e = a\, X^{-\beta}$ (suggested by the actual data) by least squares. This curve gives the expected number of pulsars N_e at each X. We computed a X^2 as

$$\chi^2 = \sum \{(N_0 - N_e)^2 / N_e\} \tag{10}$$

where the summation is over all bins above X_{edge}, and used it as a measure of the goodness of the curve fit. We repeated this exercise for successively lower values of X_{edge} where the fit becomes progressively poorer since one begins to include data from the transition region also. In Fig. 2(b) we have plotted X^2 as a function of X_{edge} along with the expected X^2 (which is the number of bins above X_{edge} minus two, for two parameters fitted) and the 95 per cent confidence upper bound on the expected χ^2. The observed χ^2 is normal at large X_{edge} and increases rapidly at smaller values, as expected. By interpolation, we obtained the value of X_{edge} where the observed X^2 just equals the 95 per cent confidence upper bound. At this value of X_{edge} the curve fitting is seen to definitely break down. We adopted this value of X_{edge} as S_0. Although this approach tends to underestimate S_0, it has the important merit of being an objective way of analysing the data. We obtain $S_0 = 7{\cdot}6$ mJy, or $\beta S_0 = 7{\cdot}9$ mJy, which is close to the quoted value of 8·0 mJy. We interpret this agreement as lending support to the validity of our approach. A similar exercise with Fig. 3(a) gives $S_0 = 6{\cdot}6$ mJy.

We then computed the width of the transition region in Fig. 2(a) using the estimate

$$\sigma_{\mathrm{tr}}^2 = \sum \{f_i (\log X_i - \log S_0)^2\} \Big/ \sum f_i \tag{11}$$

where $f_i = N_0/N_e$ is the weight in each bin. The summation in Equation (11) is taken over all bins below S_0. We obtain $\sigma_{\mathrm{tr}} = 0{\cdot}20$. For Fig. 3(a) we get $\sigma_{\mathrm{tr}} = 0{\cdot}15$. Comparing the results of Figs 2 and 3 we see that (i) the width of the transition region is reduced by incorporating the period and declination dependent selection effects through Equation (8) and (ii) there are 60 pulsars below S_0 in Fig. 2(a) but only 33 in Fig. 3(a). Both these results support our contention that Equation (8) is a better representation of the selection effects in the II MS than Equation (1).

Finally, we have repeated the calculations of Table 1 using Equation (8) with $S_0 = 6{\cdot}6$ mJy, instead of Equation (1) with $S_0 = 8$ mJy. The results are shown in Table 2. The values of σ quoted are not equal to the corresponding $n_e^{1/2}$ but have been computed by including the fluctuations as well as the correlations of all the variables entering in $(n_0 - n_e)$. We have computed a χ^2 using the estimate

$$\chi^2 = \sum_{i=1}^{3} \{(n_0 - n_e)^2 / \sigma_i^2\} \tag{12}$$

where the summation extends over all bins. We obtain $\chi^2 = 5{\cdot}0$ in Table 2(a) and $\chi^2 = 1{\cdot}2$ in Table 2(b) as against the expected value of 3. In both cases there is a clear improvement over the results of Table 1.

The various tests described above would appear to confirm the presence of the period-dependent and declination-dependent selection effects in the II MS. However, because of the noisy data, we believe the strongest argument is really the discussion of Section 2 which says such effects must exist.

Table 2. Each column shows (i) observed number of pulsars (n_0) with $S_{\text{pulsar}}/S_{\text{min}} < 1{\cdot}0$, (ii) all pulsars in that bin ($n_0 + m_0$), (iii) expected number (n_e) in that bin, (iv) the difference ($n_0 - n_e$), and (v) standard deviation (σ) on $n_0 - n_e$. S_{min} was derived using Equation (8).

	(a) Pulsars in bins of period (in seconds):			(b) Pulsars in bins of declination:		
	$0{\cdot}0 \leqslant P < 0{\cdot}5$	$0{\cdot}5 \leqslant P < 1{\cdot}0$	$1{\cdot}0 \leqslant P < 1{\cdot}5$	$0° \leqslant \delta < 30°$	$30° \leqslant \delta < 60°$	$60° \leqslant \delta < 90°$
n_0	6	15	5	15	11	7
$n_0 + m_0$	76	89	40	97	89	38
n_e	9·6	11·3	5·1	14·3	13·1	5·6
$n_0 - n_e$	−3·6	3·7	−0·1	0·7	−2·1	1·4
σ	2·3	2·4	1·9	2·6	2·6	2·0

4. Implications for injection

VN (1981) based their statistical study of pulsar data on the current J_p of pulsars (number of pulsars yr^{-1} galaxy^{-1} 'flowing' along the P-axis) in various bins of period (0·0 to 0·5 s, 0·5 to 1·0 s, *etc.*). They computed J_p using the equation

$$J_p = \sum_i \dot{P}_i \, S(L_i) \tag{13}$$

where $\dot{P}$ are the observed period derivatives and $S(L_i)$ are derived scale factors, which account for radio-luminosity selection effects. The summation in Equation (13) is over all pulsars in a given period bin. VN showed that the current averaged between 0·0 s to 0·5 s is significantly lower than that averaged between 0·5 s to 1·0 s. Since this has important implications for the understanding of pulsars, in this section we investigate whether the result is qualitatively altered when the new P-dependent and δ-dependent selection effects are included.

We have recalculated $S(L)$ using Equation (8) (by means of the Monte Carlo technique employed by VN) and obtained new scale factors $S(L, P)$, which are now a function of both luminosity and period. The ratios of the new to old scale factors are, on the average, higher by 18 per cent in the first period bin ($0 \leqslant P < 0{\cdot}5$) and by 6 per cent in the second bin ($0{\cdot}5 \leqslant P < 1{\cdot}0$), both compared to longer period bins. Obviously these changes will not affect the substantial injection noted by VN. For further confirmation, we have repeated the injection calculations for II MS pulsars alone using Equation (8) with S_0=6·6 mJy and assuming d=d_0. Fig. 4 shows the mean currents we now obtain in the various bins of P. We have here included a few additional pulsars whose $\dot{P}$ values have recently been measured with improved accuracy. It will be noticed that the currents in the first two bins continue to differ significantly. In spite of the large (95 per cent confidence) error bars, it is still quite apparent that these two currents are unlikely to be equal. We thus conclude that the new period selection effect modifies the earlier injection result only marginally.

At this stage it is worth investigating if there could be any other period-dependent selection effect not yet identified. A somewhat remote possibility lies in the measurement of $\dot{P}$ values. While the detection of a pulsar is independent of its $\dot{P}$, the later estimation of $\dot{P}$ with any significance becomes increasingly difficult at lower values of

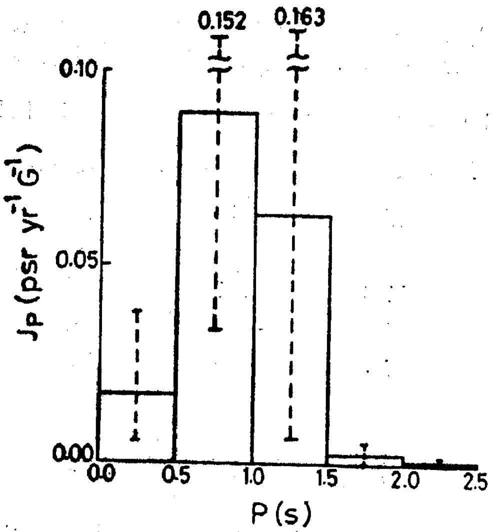

Figure 4. Mean pulsar current in bins of period for the II Molonglo Survey using Equation (8) for S_{min} (see VN for details). The current in the second bin is significantly higher than the current in the first bin, showing that injection exists in spite of the extra selection effects. The error bars represent 95 per cent confidence limits.

$\dot{P}$. Now, in the list of pulsars used for the injection calculation of Fig. 4, there are some whose $\dot{P}$ values are yet to be determined reliably. It would be interesting to know how these $\dot{P}$ values, if and when they are measured, would affect the results. We have tried to estimate this effect by binning the non-$\dot{P}$ pulsars belonging to the II MS in the same period bins as in Fig. 4. We find that the histogram of non-$\dot{P}$ pulsars is quite similar to that of the rest of the pulsars whose $\dot{P}$ are known, showing that there is no obvious period-dependence. In addition, the missing $\dot{P}$ values are more likely to be of lower magnitudes, and we have verified that the mean scales of these pulsars are approximately in the same proportions as the currents in Fig. 4. We therefore expect the effect to be marginal.

To summarize the results of this paper:

1. The period-dependent selection effect Equation (8) has been shown to exist, and the II MS data show some evidence for it. We believe the evidence is not as strong as one might like because of the small numbers we are dealing with. In addition, the II MS also shows a declination-dependent selection effect. On the other hand, there appears to be no reason to fear a period-dependent selection effect arising from the lack of measured $\dot{P}$ for some pulsars.

2. The 'injection' of pulsars pointed out by VN is affected only marginally by the additional selection effects discussed here. The qualitative result is unaltered and awaits an explanation in terms of pulsar physics.

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