Aust. J. Phys., 1979, **32**, 1–7

The Galactic Distribution of Pulsars

R. N. Manchester

Division of Radiophysics, CSIRO, P.O. Box 76, Epping, N.S.W. 2121.

Abstract

Data from the second Molonglo pulsar survey have been analysed to determine the galactic distribution of pulsars. The results show that the total number of active pulsars in the Galaxy (assuming that only 20% of these are observable because of beaming effects) is about 2×10^6. For a mean active lifetime of 10^7 years, this implies that pulsars are born at the rate of one every five years. It is also shown that there is a correlation between pulsar period and distance from the galactic plane, with long period pulsars being, on the average, more distant from the plane than short period pulsars.

1. Introduction

One of the primary aims of the second Molonglo pulsar survey (Manchester *et al.* 1978) was to detect a relatively large and well-defined sample of pulsars to provide a data base for investigations of the galactic distribution and luminosity function of pulsars. The survey was successful in that a total of 224 pulsars was detected, more than four times the number detected in any previous single survey.

In this paper I present results of a preliminary analysis of the survey data using the techniques described by Taylor and Manchester (1977). The galactic distribution is assumed to be cylindrically symmetric about the galactic axis. The number of detected pulsars having a period between P and $P+\mathrm{d}P$, a perpendicular distance from the galactic plane between z and $z+\mathrm{d}z$, a galactocentric radius between R and $R+\mathrm{d}R$ and a luminosity between L and $L+\mathrm{d}L$ may be represented by

$$N(P,z,R,L)\,\mathrm{d}P\,\mathrm{d}z\,\mathrm{d}R\,\mathrm{d}L = V(P,z,R,L)\,\rho(P,z,R,L)\,\mathrm{d}P\,\mathrm{d}z\,\mathrm{d}R\,\mathrm{d}L\,, \qquad (1)$$

where $V(P,z,R,L)\,\mathrm{d}z\,\mathrm{d}R$ represents the volume of the Galaxy between z and $z+\mathrm{d}z$ and R and $R+\mathrm{d}R$ which was searched for pulsars of period P and luminosity L, and $\rho(P,z,R,L)\,\mathrm{d}P\,\mathrm{d}L$ is the space density of pulsars having periods between P and $P+\mathrm{d}P$ and luminosities between L and $L+\mathrm{d}L$ at galactic position (z,R). Provided the distributions in P, z, R and L are uncorrelated, the density can be separated into four functions

$$\rho(P,z,R,L) = \rho_P(P)\,\rho_z(z)\,\rho_R(R)\,\rho_L(L)\,. \qquad (2)$$

Following Taylor and Manchester (1977) we adopt as a radio luminosity the parameter $L = Sd^2$, where S is the mean pulsar flux density in mJy and d is the distance in kpc.

In order to evaluate the pulsar luminosities and space densities we must have estimates of the pulsar distances. Again following Taylor and Manchester (1977), distances were computed from the dispersion measure assuming an electron density at $z = 0$ of $0\cdot03\ \mathrm{cm}^{-3}$ and an electron density scale height of 1 kpc. Allowance was made for the effect of HII regions within 1 kpc (Prentice and ter Haar 1969). Where available, distances obtained from HI absorption measurements or SNR associations were used in preference to the dispersion-derived distances. Fig. 1 shows the distribution of detected pulsars projected onto the galactic plane. Most of the detected pulsars are relatively close to the Sun; only high luminosity pulsars are detected far from the Sun.

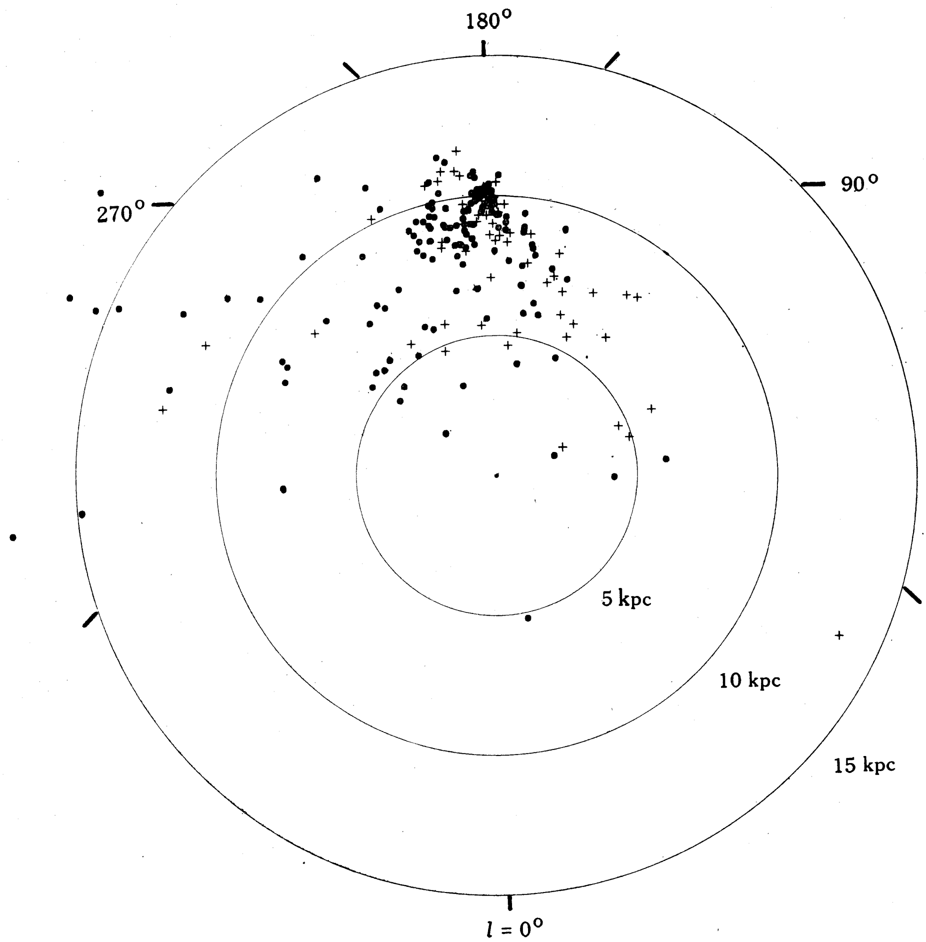

Fig. 1. Distribution of 224 pulsars detected in the second Molonglo pulsar survey projected onto the galactic plane. Previously known pulsars are marked with a cross.

2. Galactic Distribution of Pulsars

Distribution against P and z

The available evidence suggests that there is little correlation between galactic position and radio luminosity. However, the pulsars detected in the second Molonglo pulsar survey do show a correlation between their period and their z distribution.

This is illustrated in Fig. 2; pulsars with short periods are restricted to a smaller range of $|z|$ than those with long periods. Mean values of $|z|$ for pulsars in three different period ranges are as follows:

Period range (s)	No. of pulsars	$\langle |z| \rangle$ (pc)
$0 \cdot 10 < P \leqslant 0 \cdot 32$	29	190 ± 35
$0 \cdot 32 < P \leqslant 1 \cdot 00$	135	375 ± 30
$1 \cdot 00 < P \leqslant 3 \cdot 2$	58	510 ± 80

This effect is consistent with pulsars being born close to the galactic plane and then moving away during their lifetime (see Section 3).

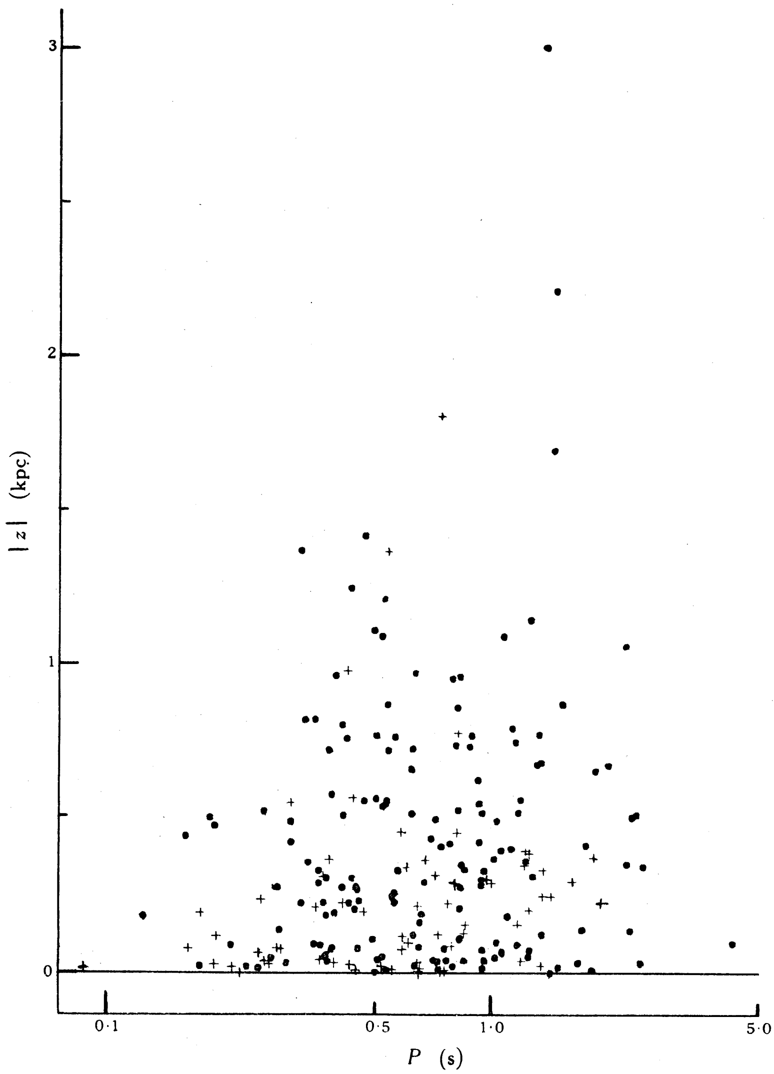

Fig. 2. Plot of perpendicular distance $|z|$ from the galactic plane versus period P for 224 pulsars detected in the second Molonglo pulsar survey. Previously known pulsars are marked with a cross.

Because of the correlation between P and z we cannot separate ρ_P and ρ_z in equation (2). Fortunately, however, the survey did not seriously select against either P or z values where pulsars are known to exist (Manchester *et al.* 1978). Consequently the volume V in equation (1) is essentially independent of P and z, that is,

$$V(P, z, R, L) = V(R, L),$$

and the observed distributions against P and z closely approximate the true distributions. Fig. 3 shows that the observed z distribution is adequately represented by an exponential distribution with a scale height of 350 pc. This is somewhat larger than values obtained in previous analyses (Davies *et al.* 1977; Taylor and Manchester 1977) owing to the greater number of long period high-z pulsars detected in the second Molonglo survey.

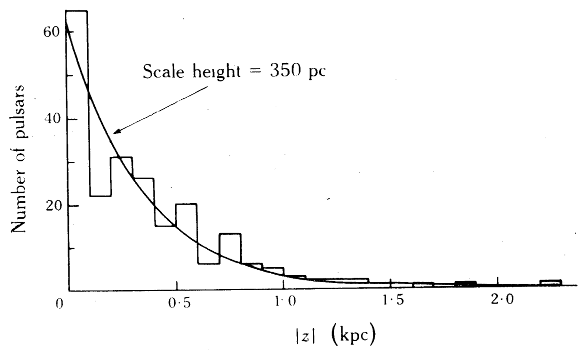

Fig. 3. Observed distribution of $|z|$ for 224 pulsars detected in the second Molonglo pulsar survey.

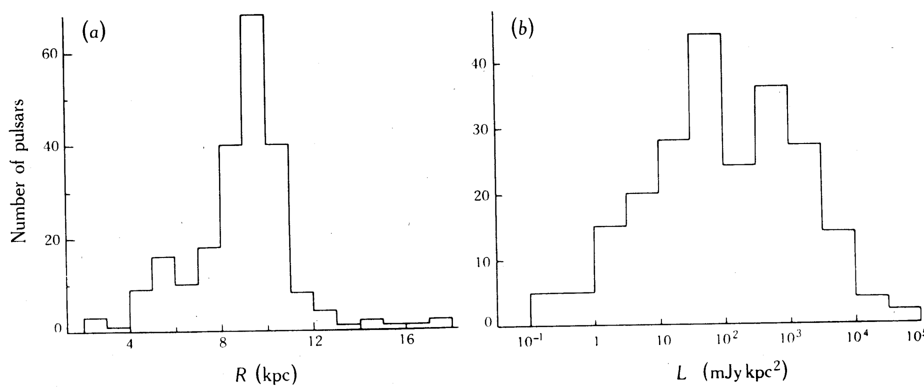

Fig. 4. Observed distributions of (*a*) galactocentric radius R and (*b*) radio luminosity L for 224 pulsars detected in the second Molonglo pulsar survey.

Distribution against R and L

The observed distributions against galactocentric radius R and radio luminosity L are shown in Figs 4*a* and 4*b*. These two distributions are strongly affected by selection since low luminosity pulsars are detected only if they are relatively close to the Sun. This accounts for both the strong peak at galactocentric radii of about

10 kpc (Fig. 4*a*) and the falloff with decreasing luminosity in the number of pulsars detected (Fig. 4*b*).

Following Taylor and Manchester (1977), the function $V(R, L)$ for the second Molonglo survey was computed by a Monte Carlo method. Limiting flux densities S_{min} for sample points within the Galaxy were computed using the relation

$$S_{min} = \beta S_0(1 + T_{sky}/T_r)(1 + DM/DM_0)^{\frac{1}{2}}, \tag{3}$$

where the minimum detectable flux density $S_0 = 8$ mJy, the receiver temperature $T_r = 210$ K and, for the low latitude part of the survey ($|b| < 18°$), the limiting dispersion measure $DM_0 = 780\ \mathrm{cm^{-3}\,pc}$ while, for the high latitude part, $DM_0 = 130\ \mathrm{cm^{-3}\,pc}$. Since the survey consisted of overlapping drift scans on 2°·5 centres with a beamwidth in declination of 4°·3, the beam factor β was obtained by randomly choosing a direction within 1°·25 of the beam centre and computing the relative gain assuming a gaussian beam shape.

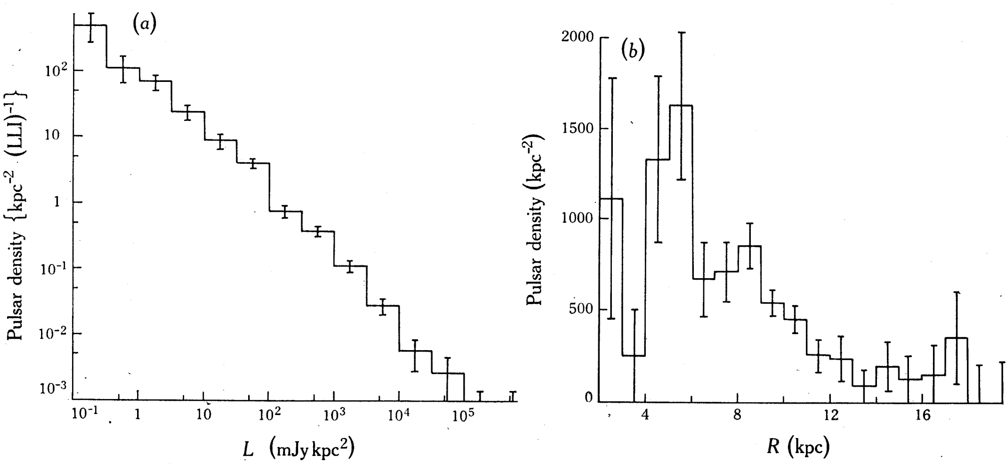

Fig. 5. Derived distribution functions for 224 pulsars in the second Molonglo pulsar survey:

(*a*) Luminosity function for pulsars in the local region ($R \sim 10$ kpc). The ordinate gives the density of pulsars projected onto the galactic plane per logarithmic luminosity interval (LLI).

(*b*) Distribution of pulsars against galactocentric radius R.

Error bars denote $\pm\sigma$ and represent statistical errors only.

Equation (1) was solved using an iterative technique to derive the logarithmic luminosity function $\Phi(L) = L\rho_L(L)$ and the radial distribution $\rho_R(R)$. The derived luminosity function in the solar neighbourhood, shown in Fig. 5*a*, increases monotonically toward lower luminosities with no sign of a low luminosity cutoff. To find the area density $D(10)$ of pulsars projected onto the galactic plane at $R = 10$ kpc, we can sum this luminosity function. Assuming that no pulsars with $L < 0{\cdot}1\ \mathrm{mJy\,kpc^2}$ exist, we have

$$D(10) = 510 \pm 180 \quad \mathrm{kpc^{-2}}. \tag{4}$$

The quoted error represents the statistical uncertainty; the systematic uncertainties are likely to be at least as great. Pulsars with $L < 0{\cdot}1\ \mathrm{mJy\,kpc^2}$ may exist, and clearly this would increase the value of $D(10)$. A high sensitivity survey covering a considerable area of the sky, preferably at high galactic latitudes, would be required to detect a significant number of these pulsars. There are two main effects which could result in our overestimating $D(10)$. Firstly, some pulsars may have been detected in a transient peak of activity. For these pulsars, the true limiting flux density is less than the assumed value and hence the derived densities are too large. The question of completeness of the survey is a difficult one, requiring some knowledge of the statistics of pulsar intensity variations. Secondly, the assumed value of $0 \cdot 03$ cm^{-3} for the interstellar electron density $\langle n_e \rangle$ may be too large. If distances are underestimated, particularly for the nearby and high latitude pulsars, then the derived densities will be too great. The adopted electron density is based on observations of rather distant pulsars (e.g. Ables and Manchester 1976); however, Hα observations (Reynolds 1977) suggest that, if anything, the electron densities are actually larger than $0 \cdot 03$ cm^{-3} in the local region.

The derived distribution of pulsars against galactocentric radius is plotted in Fig. 5*b*, the ordinate being scaled according to equation (4). As found in previous work (Davies *et al.* 1977; Taylor and Manchester 1977), the density of pulsars is a decreasing function of galactocentric radius, at least for $R \gtrsim 6$ kpc. For the inner part of the Galaxy, the statistics are very poor and no conclusion can be drawn from these results.

The total number of potentially observable pulsars in the Galaxy may be found by integration

$$N_G = 2\pi \int_0^\infty R D(R)\, dR. \tag{5}$$

Using the data shown in Fig. 5*b*, we obtain $N_G = (4 \cdot 2 \pm 1 \cdot 6) \times 10^5$, where the quoted error represents purely the statistical uncertainty. If only 20% of all pulsars are detectable because of beaming effects then the total number of active pulsars in the Galaxy is of the order of 2×10^6.

3. Pulsar Birthrate

In order to find the rate at which pulsars are born in the Galaxy, we must have some estimate of the average time a pulsar spends in the active phase. There are two independent approaches to this problem: the first is based on the fact that pulsars are high velocity objects and the second is based on the observed distribution of characteristic ages (Taylor and Manchester 1977; Davies *et al.* 1977). If pulsars are formed near the galactic plane and move away during their lifetime then their mean age is given by

$$\langle \tau \rangle = \langle |z| \rangle / \langle |v_z| \rangle, \tag{6}$$

where $\langle |v_z| \rangle$ is the mean value of the velocity component perpendicular to the galactic plane. Observations of pulsar proper motion (Manchester *et al.* 1974; Anderson *et al.* 1975; Backer and Sramek 1976; Wyckoff and Murray 1977) suggest that pulsars typically have transverse velocities of the order of $150\ km\,s^{-1}$, which implies $\langle |v_z| \rangle \approx 150/\sqrt{2} \approx 100\ km\,s^{-1}$. For the entire sample of pulsars we have $\langle |z| \rangle \approx 350$ pc, so that their mean age $\langle \tau \rangle \approx 3 \cdot 5 \times 10^6$ yr. Their mean active lifetime is just twice this value, or $\sim 7 \times 10^6$ yr, which is in good agreement with the value of $\sim 5 \times 10^6$ yr derived from the observed distribution of characteristic ages (Davies *et al.* 1977; Taylor and Manchester 1977).

To be conservative, we adopt a mean active lifetime for pulsars of 10^7 years. The birthrate required to produce a population of 2×10^6 active pulsars is then $2 \times 10^6/10^7 = 0 \cdot 2\ \mathrm{yr}^{-1}$, or one pulsar birth every 5 years. There are considerable uncertainties in this value. Considering these uncertainties, the derived rate is not inconsistent with Tammann's (1977) estimate of the average rate at which supernovae occur in the Galaxy, namely once every 11^{+14}_{-4} yr. However, the present value does appear to be inconsistent with computed rates of formation of shell-type SNRs (Caswell and Lerche 1979, present issue pp. 79–82; Milne 1979, present issue pp. 83–92). Taken at face value, it requires that all stars with mass greater than about $2 \cdot 5$ solar masses must end their evolution as pulsars. If we further assume that the rate of stellar formation and evolution has been constant over the past 10^{10} yr then it also implies that the Galaxy has a halo population of more than 10^9 dead pulsars. The total mass of this population could be several per cent of the total mass of the Galaxy.

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Manuscript received 5 July 1978