X. GALACTIC DISTRIBUTION OF PULSARS

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THE GALACTIC DISTRIBUTION OF PULSARS

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ABSTRACT

The galactic distribution of pulsars follows the general form of many population I objects in galactocentric radius, but has a wide distribution above and below the galactic plane due to high space velocities imparted to the pulsars at birth. The evidence for this model is described and the various factors involved in estimating the total galactic population and the galactic birthrate of pulsars are discussed. The various estimates of the galactic population which cluster around 5×10^5 are seen to be critically dependent upon the cut-off at low luminosities and upon the value of the mean electron density within 500 pc of the Earth. Estimates of the lifetimes of pulsars are available from both the characteristic ages and proper motion measurements and both give values of about 5 million years. The implied birthrate of one in every 10 years is barely compatible with most estimates of the galactic supernova rate.

1. INTRODUCTION

At the present time there are 328 known pulsars, the majority having been discovered in the four main surveys carried out at Arecibo, Jodrell Bank and Molonglo, all at frequencies of about 400 MHz (Hulse and Taylor, 1974, 1975; Davies, Lyne and Seiradakis, 1972, 1973; Large and Vaughan, 1971 and Manchester et al. 1978). The main characteristics of these surveys are shown in Table 1. As the number of known pulsars has increased so have the number of attempts at assessing the distribution of pulsars through the Galaxy and the galactic birthrate required to sustain the observed population.

Figure 1 shows a plot of the known pulsars in galactic coordinates, and the concentration of pulsars along the galactic plane is clear. Although there is now a fairly good coverage of the whole sky, the depth of coverage is not completely uniform. For instance, the high density of pulsars around longitude 50° is due to the very deep Arecibo

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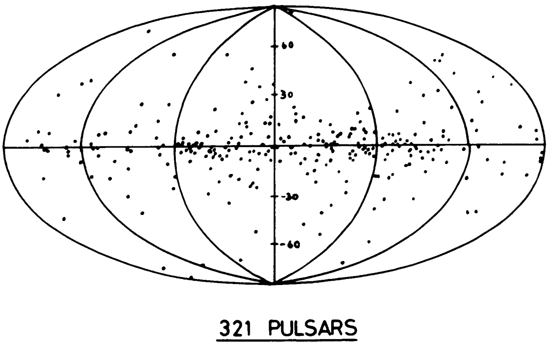

Figure 1: The distribution of pulsars in galactic coordinates

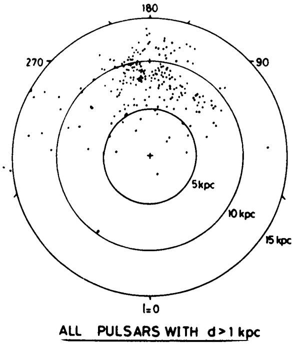

Figure 2: The distribution of pulsars projected onto the galactic plane

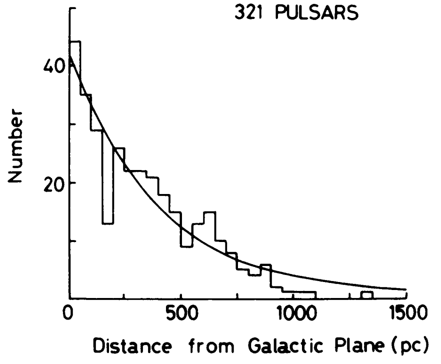

Figure 3: The observed z-distribution of 321 pulsars

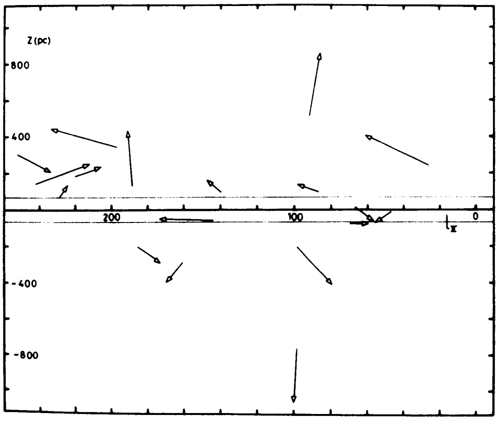

Figure 4: The velocity vectors of 18 pulsars plotted as a function of galactic longitude and z-distance. The pulsar's position is at the back of the arrow. The length of the arrow represents the velocity, the largest being 500 km s^{-1}.

Table 1 THE MAIN PULSAR SURVEYS

	Area surveyed	No of new pulsars	No of Pulsars detected
1st Molonglo	7 sr	31	34
Jodrell Bank	1 sr	39	51
Arecibo	0.055 sr	40	49
2nd Molonglo	8 sr	155	224

survey which covered only a very limited area of sky close to the galactic plane. The low density of pulsars towards the centre of the Galaxy is due, at least in part, to the reduced receiver sensitivities caused by the very high galactic background noise contribution. The removal of these and other selection effects is of paramount importance in the investigation of the galactic distribution. The aim of this paper is to summarise some of the arguments employed in these studies and to try and give some indication of the reliability of the calculations and conclusions.

2. THE DISTANCE SCALE

In order to study the distribution of pulsars through the Galaxy, it is necessary to know their distances and fortunately the dispersion measure provides an approximate indicator when combined with some model of the galactic distribution of electrons. Also, independent distance estimates can be obtained for a number of pulsars, allowing a calibration of the mean value of the electron density, n_e, in the interstellar medium. The main independent distance estimates are obtained from the absorption of the 21 cm radiation from the pulsar by interstellar HI when combined with a model for the differential rotation of the Galaxy. Such observations have been carried out for about 30 objects.

Using these distance estimates, it is found that over the lines of sight to pulsars out to distances comparable with the radius of the Galaxy, the mean value of the electron density is close to 0.03 cm^{-3}. See for example Graham et al. (1974), Ables and Manchester (1976) and Booth and Lyne (1976).

The electrons responsible for most of this dispersion seem to be distributed through the general interstellar medium and to have a scale height in z-distance, the height above or below the plane, which is comparable with or greater than that of the pulsars (Taylor and Manchester 1977, Davies, Lyne and Seiradakis 1977) which as we shall see amounts to a few hundred parsecs.

However, as first pointed out by Prentice and ter Haar (1969), discrete HII regions along the line of sight contribute significantly to the dispersion measure. Within 1 kpc of the Sun it is possible to identify individual HII regions and to estimate their electron content. It is found that the mean density of the electrons in this distribution of HII regions approximates in z-distance, to an exponential of scale height 70 pc having a central density on the plane of 0.015 cm^{-3}. This leads to a model of the electron distribution from which pulsar distances may be calculated in which there is a uniform mean electron density of 0.025 cm^{-3} together with an exponential of scale height 70 pc and central density of 0.015 cm^{-3}. However, within 1 kpc, this exponential is replaced with the individual HII regions. This model still satisfies the HI absorption measurements and is the one used by Manchester (1979) recently.

Hall (1980) has recently provided a useful survey of our knowledge of the electron distribution in the Galaxy and from a study of the pulsar dispersion measure data arrives at a similar model involving a concentration in the plane having a central density of 0.048 cm^{-3} and an exponential scale height of 264 pc. The effect of these models upon the derived pulsar distributions will be discussed later.

3. THE OBSERVED DISTRIBUTIONS AND VELOCITIES

Using the distance estimates either from the HI absorption observations or from the dispersion measures and the model of Manchester (1979), Figure 2 shows the positions of the pulsars projected onto the galactic plane, where the Sun is assumed to be at a distance of 10 kpc from the galactic centre. We note the strong selection effect caused by the inverse square law and it is also obvious that there are more pulsars within the solar circle than outside it.

Figure 3 shows the observed z-distance distribution which also contains a number of selection effects, the most important being a reduction in sensitivity to low z-distance pulsars because of the high galactic background radiation at low latitudes. We see an approximately exponential distribution having a scale height of 400 pc, substantially greater than that of most massive stars which are likely to be the progenitors of pulsars, and also than that of supernova remnants, both having scale heights of about 70 pc. Gunn and Ostriker (1970) provided the explanation for this as pulsars being runaway stars which have moved larged distances since birth. This can now be seen quite explicitly from recent proper motion measurements on 26 pulsars using interferometry at Jodrell Bank (Lyne, Anderson and Salter 1980).

In Figure 4 the significant proper motions have been converted to velocities using the pulsar distance estimates and are shown as a function of galactic longitude and galactic z-distance. It is clear that with one exception all the pulsars outside a "progenitor" layer of width of about 70 pc above and below the galactic plane are migrating away from the plane. The one exception is PSR 1237+25 which lies very close to the galactic pole so that the observed transverse motion is dominated by the velocity component parallel to the galactic plane. The mean transverse velocity is about 145 km s^{-1} for the whole of the Jodrell sample (assuming those with only upper limits to have zero proper motion) and corresponds to a Maxwellian distribution having a velocity dispersion of 120 km s^{-1}. This compares with estimates from previous, smaller samples of pulsars of 130 km s^{-1} (Taylor and Manchester 1977), 150 km s^{-1} (Helfand and Tademaru 1977) and 70 km s^{-1} by Hanson (1979). These smaller samples were certainly influenced by some extent by a selection tendency towards large proper motions, and the work of Hanson (1979) attempted to take into account the effects of the selection which now seem to have been rather over-estimated.

The mean component of velocity normal to the galactic plane is close to 100 km s^{-1} from the data of Lyne, Anderson and Salter (1980), and the deduced mean space velocity of the pulsars in the sample is 180 km s^{-1}.

From the distance of a pulsar, d, and its observed radio flux density at 400 MHz, it is possible to compute a luminosity parameter,

$$L = S_{400}d^2$$

In Figures 5 and 6 are shown the observed distributions in this luminosity, L, and in the galactocentric radius, R, both of which are of course severely affected by selection effects.

4. THE DERIVED GALACTIC DISTRIBUTIONS

The main selection effects at play in Figures 3, 5 and 6 are due to the inverse square law, the areas of the sky surveyed and the changing receiver sensitivity due to the galactic background noise variations across the Galaxy. Various attempts have been made to remove those selection effects and to derive the true distributions in the three main parameters L, R and z.

All pulsar surveys have a limiting flux density below which pulsars are undetectable and this effectively limits the volume of Galaxy searched for pulsars of a given luminosity. It is however, possible to calculate the volume of Galaxy in a given survey searched for pulsars having a luminosity, L, and lying between R and R+dR and z+dz. From the number observed and the volume of space searched it is then possible to calculate a space density for pulsars at a particular L, R and z. This approach has been used firstly by Large (1971) and later by Davies, Lyne and Seiradakis (1977) and Taylor and Manchester (1977) in analyses based upon samples of increasing size.

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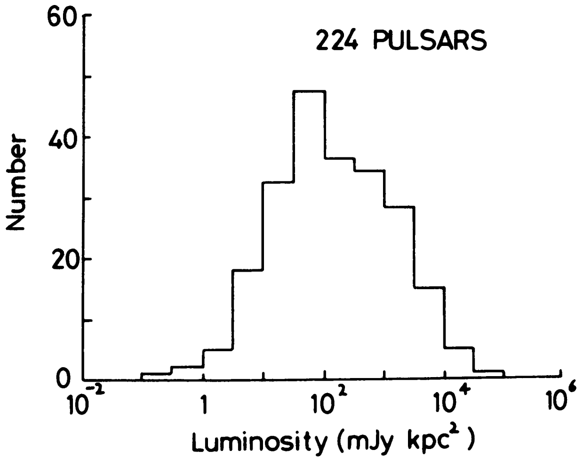

Figure 5: The observed luminosity distribution

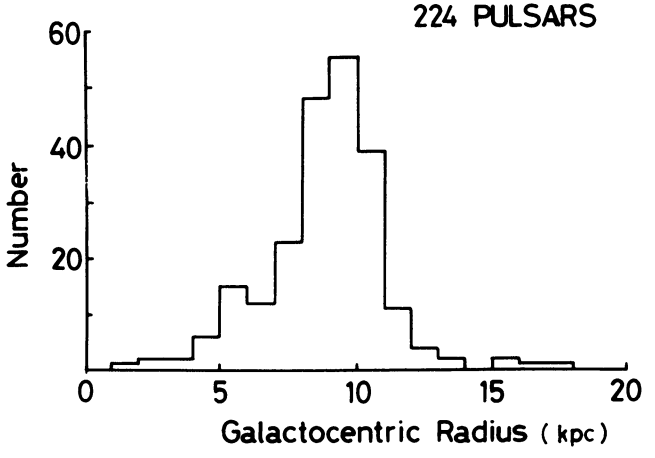

Figure 6: The observed galactocentric radius distribution

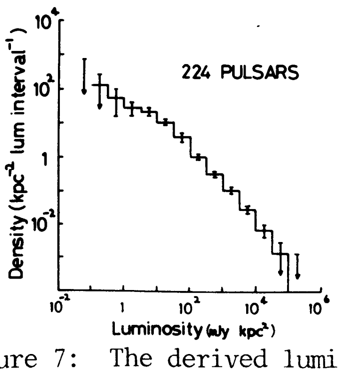

Figure 7: The derived luminosity distribution

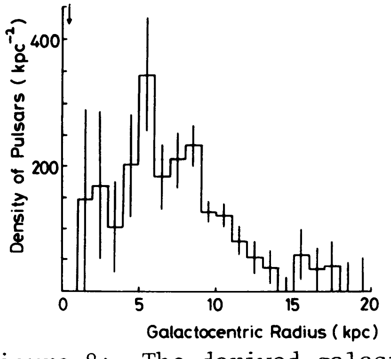

Figure 8: The derived galacto-centric radius distribution

More recently, Manchester (1979) has carried out such an analysis on the 224 pulsars detected in the Molonglo Survey (Manchester et al. 1978) and his results are summarised for the distributions in L and R in Figures 7 and 8. The luminosity distribution in Figure 7 shows the density of pulsars at the position of the Sun as the number of pulsars in each semi-decade range of luminosity per square kiloparsec of the plane. This plot increases steadily with decreasing luminosity and although it shows signs of flattening at low luminosities there is no well-defined low luminosity cut-off, so that it is possible only to derive a lower limit on the total density of pulsars. However, assuming that there are no pulsars with luminosity less than 0.3 mJy kpc^2 (although one weaker than this has in fact been observed) then integration under this curve gives a density of 125 ± 40 observable pulsars kpc^{-2} at the position of the Sun (R = 10 kpc).

The galactocentric radial distribution in Figure 8 is a strong function of radius, R, and shows a marked resemblence to that of supernova remnants and HII regions and probably also of massive stars. It is reassuring that the distribution varies reasonably continuously through the position of the Sun (R = 10 kpc) showing that the powerful selection effects responsible for the peak in Figure 6 have been substantially removed by the analysis.

These distributions have not changed greatly in general form since Large (1971) carried out the first analysis, even though the size of the statistical sample has increased by nearly a factor 10. The main improvements have been in the statistical uncertainties throughout the R distribution and at the low luminosity end of the L distribution.

The total number of observable pulsars is obtained by integrating the distribution in R through the galactic disc and gives a value of $(1.0 \pm 0.4) \times 10^5$. Note that the rather poorly determined density near the galactic centre does not affect the accuracy of this value much because of the relatively small volume of space involved. However, because of geometrical effects, we can expect to observe only a small fraction, f, of all the active pulsars in the Galaxy, i.e. those whose radiation beams cross the Earth during a rotation of the pulsar. If the radiation beams have the same width in latitude as in longitude (and for most polar cap models this is the case) then $f \sim 0.2$. For most relativistic beaming models it seems that a similar value of f is also appropriate. Certainly, it is difficult to see how a value of f much less than this can come about. Adopting a value for f of 0.2, then the total number of active pulsars in the Galaxy is

$$(5 \pm 2) \times 10^5 .$$

Table 2 summarises the results of some of the studies by a number of authors on various samples of pulsars using a number of analysis methods and shows a moderate agreement in the total number of active

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Table 2 Estimates of the Galactic Population and Birthrate

	Sample (note 1)		n_e (note 2) (cm^{-3})	h_e (note 2) (pc)	L_{min} (mJy kpc^2)	N_G	$1/\dot{N}_G$ (years)
Large (1971)	31	M1	0.05	∞	1.6	$5x10^5$	-
Davies et al. (1977)	51	J	0.025	∞	1.6	$4x10^5$	2-18
Taylor and Manchester (1977)	90	A+J	0.03	1000	3	$1x10^5$	6
			0.02	1000	3	$6x10^5$	40
Guseinov and Kasumov (1978)	105	All	0.03	1000	6	$0.8x10^5$	24-74
Gailly et al. (1978)	224	M2	0.025	∞	-	$(0.4-13)x10^5$	7-149
Manchester (1979)	224	M2	0.015	70 }	0.3	$5x10^5$	20
			0.025	∞			
Arnaud and Rothenflug (1980)	116	M2	-	-	3	$0.6x10^5$	70-160

Note 1 The size and survey of origin of the sample used as follows:
A Arecibo (Hulse and Taylor, 1974, 1975)
J Jodrell Bank (Davies, Lyne and Seiradakis, 1977)
M1 First Molonglo (Large and Vaughan, 1971)
M2 Second Molonglo (Manchester et al., 1978)

Note 2 The central density and scale height of the electron distribution of the model used in the analysis.

pulsars in the Galaxy. Note that the definition of "active" here varies from paper to paper but is essentially that the pulsar has a luminosity greater than some value L_{min}. The values chosen for L_{min} by the authors are given in the table and it is this critical choice which is primarily responsible for the dispersion in the estimates of the size of the galactic population. For instance, Arnaud and Rothenflug (1980) have obtained an estimate of 0.6×10^5 pulsars using a rather different approach to that described here applied to a subset of the Molonglo survey. Their method involves the fitting of a model to the observed flux density and galactic longitude distributions and has the virtue that it relies only upon distance estimates based upon HI absorption measurements. However the method is very insensitive to any low-luminosity cut-off in the pulsar luminosity function and the value of 3 mJy kpc^2 for L_{min} is somewhat arbitrary and it is this choice which is substantially responsible for the low total population derived. It should be noted that although only about 4% of the observed pulsars have luminosities between 0.3 and 3 mJy kpc^2, their number is consistent with the luminosity function extending down to 0.3 mJy kpc^2. The small number of pulsars observed in this omitted luminosity range represents between 80 and 90 percent of the galactic population. This highlights the fact that the pulsars observed from the Earth are mostly a small minority of very high luminosity objects which have a mean luminosity of about 100 times the mean luminosity of the galactic population (see Figures 5 and 7).

We see therefore that the estimates of the galactic population rely heavily upon the statistical measurements of only a small number of low luminosity pulsars which lie within a few hundred parsecs of the Sun. They are too close for HI absorption measurements to determine their distance and unfortunately we have had to rely upon the dispersion measure as described in section 2. However, both Lyne (1974) and Hall (1980) have concluded that the local mean electron density is similar to that elsewhere in the Galaxy and provided that this is the case the population estimates will not be greatly in error. In fact if Hall (1980) is correct and the electrons are more closely confined to the plane than previously thought, many of the low luminosity pulsars are even closer than previous models have suggested and the population figures will have to be revised upwards. The recent measurement of the trigonometric parallax on PSR 1929+10 (Salter, Lyne and Anderson 1979), one of the low luminosity pulsars, indicates a mean electron density of 0.069 cm^{-3} and lends some support to Hall's model.

5. THE LIFETIMES AND BIRTHRATE OF PULSARS

In order to determine the birthrate of pulsars which is required to sustain the galactic population, it is necessary to investigate the lifetimes of pulsars. For this study estimates of the ages of pulsars are required and there are two approaches which have been used,

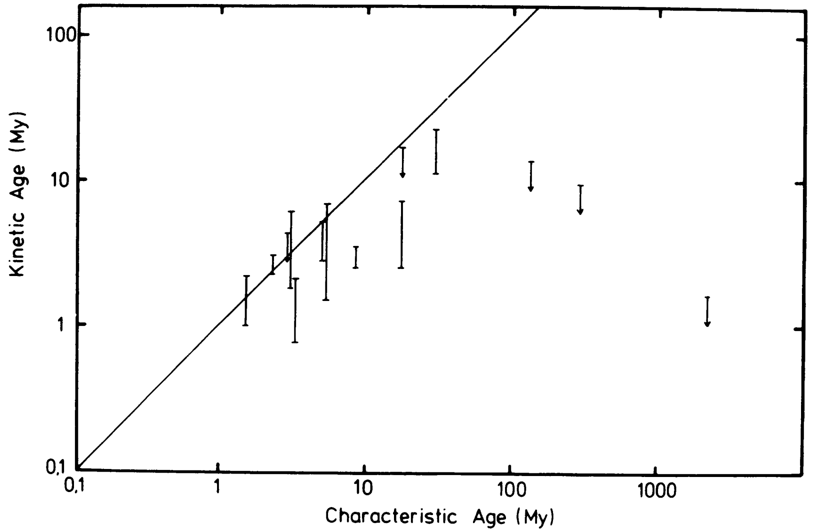

Figure 9: The kinetic age plotted against the characteristic age for 14 pulsars

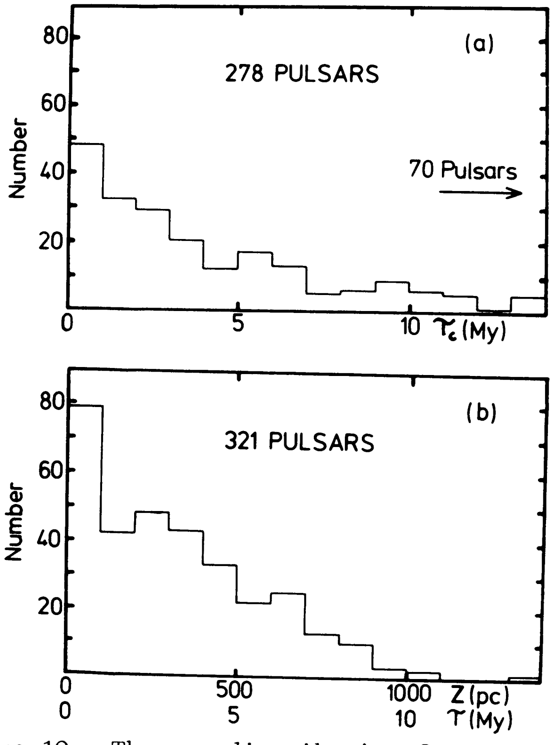

Figure 10: The age distribution for pulsars: a) from the characteristic age and b) from the z-distribution and a migration velocity of 100 km s^{-1}

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one involving the characteristic ages determined from period derivatives and one involving the z-distribution and the migration velocity determined from the proper motion measurements.

The characteristic age, $\tau_C = (P/2\dot{P})$, seems not to be a direct indicator of age for ages greater than a few million years (Lyne, Ritchings and Smith 1975, Taylor and Manchester 1977), due to either magnetic field decay or to a realignment of the magnetic and rotational axes. This has recently been established from proper motion measurements by Lyne, Anderson and Salter (1980) in which the 'kinetic age' is calculated by extrapolating the proper motion of a pulsar backwards to that point where the path intersects the galactic plane. Figure 9 shows the estimates of this kinetic age plotted against the characteristic ages for 14 pulsars. There is clearly a good overall agreement for pulsars having characteristic ages less than about five million years. For characteristic ages greater than this, the characteristic age is clearly an overestimate of the true age. In view of this, the distribution of characteristic ages for 278 pulsars shown in Figure 10a is probably reasonably accurate for the younger pulsars. Pulsars are born close to the origin of this diagram and move to the right at one year per year initially and then more rapidly as the effective magnetic field of the pulsar decays after a few million years, causing the rather wide extension to large characteristic ages. The extent of this histogram is also of course determined by the luminosity evolution of the objects, causing pulsars to disappear from the diagram as the falling luminosity reduces the observed flux to below the detection threshold.

From Figure 10a it can be seen that a birthrate of 48 pulsars in a million years is necessary to sustain a total observed population of 278 pulsars and leads to an estimate of the mean lifetime of 5.8 million years. Note that this estimate relies only upon the use of the characteristic age for ages of less than one million years where it seems to be reasonably reliable. However, some pulsars may be born with a finite period and hence finite characteristic age, and also the luminosity of some pulsars may have fallen within one million years of their birth so that they are now below the level of detection. Both of these effects will cause the 48 pulsars to be an underestimate of the number of pulsars observable from the Earth which were born within the last million years, and hence the 5.8 million year lifetime should be regarded as an upper limit.

We can also estimate the lifetime on the assumption that pulsars are born close to the galactic plane (as indicated by the proper motion observations) and interpret their height off the plane as a measure of their mean age since we know the mean migration velocity. Thus the distribution of $|z|$ in Figure 10b can be considered like Figure 10a as an age distribution. Thus a birthrate of 79 pulsars in a million years is necessary to sustain a total observed population of 321 pulsars and leads to an estimate of the lifetime of 4.0 million years in satisfactory agreement with the upper limit of 5.8 million years.

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Note that this estimate is independent of the assumed value of n_e since both the migration velocity and the scale of z-distribution depend inversely upon the assumed value of n_e.

We therefore adopt a value of 5.0 million years. This is close to the estimates of 4.5 million years by Davies, Lyne and Seiradakis (1977) using similar arguments on rather poorer data and of 4 million years by Taylor and Manchester (1977), although somewhat less than the 5-10 million years determined by Helfand and Tademaru (1977) from a sample of 12 pulsars with measured proper motions.

In order to sustain the population of 5×10^5 pulsars which have lifetimes of 5×10^6 years, we therefore need a birthrate of one pulsar every 10 years.

This rate is somewhat greater than some of the other estimates given in Table 2, but the discrepancies are mostly understandable in terms of differences in the distance scales, the low luminosity cut-off and in the lifetimes derived or used in the analyses.

6. DISCUSSION AND CONCLUSION

The pulsar birth-rate of one every 10 years involves a number of observational uncertainties and may be in error by up to a factor of three in either direction. There are five main areas which must be studied in more depth before a more secure estimate can be made:

1) The low luminosity cut-off. The estimate of L_{min} is very uncertain and it is assumed that no pulsars are less luminous than this.

2) The beaming factor.

3) The lifetimes. The low luminosity pulsars, the most numerous in the Galaxy, may have much longer lifetimes than the majority of the observed pulsars.

4) A possible preferential selection in surveys of scintillating sources. These are mostly nearby, low luminosity pulsars which may therefore be overcounted.

5) The local mean electron density.

The rate of one every ten years is uncomfortably high from a number of aspects. In particular, if all pulsars are born in supernova events, then we would expect the galactic supernova rate to be at least as great as that for pulsars. However, estimates of the supernova occurrance rate in the Galaxy range from one every few hundred years to about one every 20 years (Clark and Stephenson, 1977 and Caswell and Lerche, 1979) and observations of supernovae in other galaxies also suggest a rate of about one every 20 years (Tammann 1977). These rates are just about reconcilable with the pulsar birth rate, but almost every supernova event would have to produce a pulsar.

Although it is now generally accepted that pulsars are formed in the supernovae of massive stars, the direct experimental evidence for this is not very convincing and there are certainly some problems with this hypothesis. The main evidence is the almost incontrovertible association of the pulsars PSR 0531+21 and PSR 0833-45 with the Crab Nebula and Vela supernova remnants respectively because of the positional agreements and similarity of ages. The supernova events also provide a theoretically acceptable formation mechanism as well as an explanation for the rather high space velocities of pulsars and the small number in binary systems. The similarity in the galactic radial distributions of pulsars and supernova remnants also provides some weak circumstantial evidence, although there are many other populations of galactic objects which have the same distributions. However, the apparent incompatibility of the galactic pulsar birthrate and supernova rate suggests that not all pulsars are born in supernova events. It is just possible that the rates can be made compatible in which case if supernovae are solely responsible for pulsar production, every supernova must produce an active radio pulsar. Incidentally, if the pulsar birthrate is correct, then studies of the mass function and birthrate of stars in the solar neighbourhood suggest that all stars more massive than about 5 $M_{\odot}$ must form pulsars.

In conclusion, from the evidence as it stands, we must be prepared to question whether all pulsars are born in supernovae, or whether they may not be born in rather less violent and less obvious events, but nevertheless violent enough to provide high space velocities and disrupt most binary systems.

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