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Pulsar Velocities

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Abstract. Radio pulsars have long been established as having high velocities that are probably produced in the violence of their formation in Supernovae (Gunn & Ostriker 1970; Lyne, Anderson & Salter 1982). Three recent developments have resulted in a reassessment of their velocities: the adoption of a new distance scale (Taylor & Cordes 1993), many new determinations of proper motion (Harrison, Lyne & Anderson 1993; Bailes et al. 1989; Fomalont et al. 1992) and the realisation (Harrison & Lyne 1993) that estimates of speeds derived from scintillation measurements were systematically low by about a factor of 2. Taking into account a strong selection effect that makes the observed velocities unrepresentative of those acquired at birth, it seems that the mean space velocity of pulsars at birth is 450 ± 90 km s^{-1} (Lyne and Lorimer 1994), about a factor of 3 greater than earlier estimates. The general migration from the Galactic plane is consistent with birth in the supernova of massive Population I stars. An outstanding question is how such velocities are produced in the kinetics of supernova collapse. This large increase in birth velocity is likely to have a major impact upon our understanding of the retention of neutron stars in binary systems, globular clusters and the Galaxy as it exceeds or is comparable with all their escape velocities. The rapid spatial separation of fast and slow pulsars will have a profound effect upon calculations of the galactic population and birth rate, both of which have been underestimated in the past. Furthermore, the distribution of dead neutron stars will be more isotropic and may better match the distribution of the gamma-ray burst sources. A small number of pulsars are at a large distance from the Galactic plane, but moving towards it. The most likely origin of these objects lies in OB runaway stars.

1. Introduction

The space velocities of pulsars are important indicators of their formation process and ages. They also have important implications for the evolution of the observed population and the subsequent distribution of neutron stars in the Galaxy. Considerable technical effort over the past 20 years has now resulted in estimates of the transverse velocities of about 15% of the known pulsar population, mostly for bright and nearby objects. Since pulsars have no spectral features of known frequency their radiation, their radial velocities are unknown and individual 3-D space velocities cannot be obtained, although they can be studied in a statistical sense.

2. Velocity Measurement Techniques

The transverse velocities V_t of pulsars can be estimated using two methods, one based upon angular proper motion measurements, the other upon the measurement of the velocity of the interstellar scintillation pattern of the pulsar radiation. The first method is more accurate but requires a long series of precise observations using a high-resolution radio interferometer or accurate timing data, while the second can be carried out using a single telescope for perhaps an hour and can be applied to large numbers of pulsars.

The transverse speed of a pulsar may be calculated from its proper motion μ (mas yr^{-1}) and distance D (kpc):

$$V_{\mathrm{pm}} = 4.74 \mu D \ \mathrm{kms}^{-1}. \tag{1}$$

Measurements of proper motion from timing observations are prone to the effects of timing noise and, with the exception of millisecond pulsars, are usually less precise than direct astrometric techniques. Pulsar proper motions are now available from high-resolution interferometry for a total of 87 pulsars (Lyne, Anderson & Salter 1982; Bailes et al. 1989; Fomalont et al. 1992; Harrison, Lyne & Anderson 1993).

It was recognized soon after the discovery of pulsars that the interstellar scintillation properties of pulsar radiation (Scheuer 1968; Rickett 1970) might allow the transverse speed of a pulsar to be measured from the speed of the scintillation pattern as it moves across the Earth. Initially this was carried out using spaced receiver observations (Galt & Lyne 1972; Slee et al 1974), but later it was realized that it was possible to estimate the pattern speed from the fading time of the scintillation pattern, using a single telescope (Lyne & Smith 1982).

The speed of the interstellar scintillation pattern across the Earth, V_{iss}, is usually (Lyne & Smith 1982; Cordes 1986) calculated from the characteristic bandwidth $\Delta \nu_{\mathrm{iss}}$ (MHz) and characteristic time-scale $\Delta \tau_{\mathrm{iss}}$ (s) observed at a radio frequency ν (GHz):

$$V_{\mathrm{iss}} = A \times (\Delta \nu_{\mathrm{iss}} D)^{0.5} / (\nu \, \Delta \tau_{\mathrm{iss}}) \ \mathrm{kms}^{-1}. \tag{2}$$

The constant A depends upon the spatial power spectrum of the irregularities and the distribution of scattering material along the line of sight between the pulsar and the Earth. It is estimated by Cordes (1986) to have a value of 1.27×10^4 for a Kolmogorov spectrum, provided that the scattering irregularities are uniformly distributed along the line of sight. In this case, the speed of the scintillation pattern relative to the scattering medium will be equal and opposite in direction to that of the pulsar, and the qualitative behaviour of the scintillation pattern can be described by the thin-screen approximation (Scheuer 1968). Lyne & Smith (1982) used this method of speed determination and compared the results with those found by Lyne, Anderson & Salter (1982) from interferometric proper motion measurements. Although they noted some systematic departures, they confirmed that the scintillation method was valid and that it is largely the pulsar motion which determines the rate of scintillation, rather than instability in the pattern caused by shearing motions within the medium.

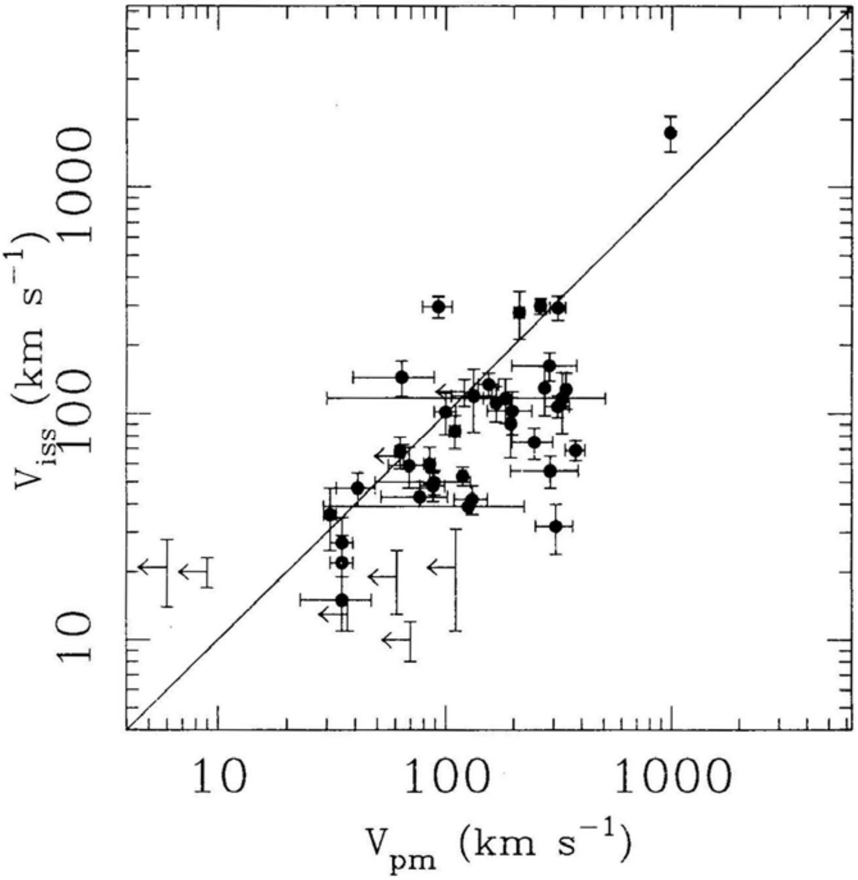

Figure 1: The transverse speeds of pulsars obtained from scintillation measurements V_{iss} plotted against those determined from proper motion V_{pm} (After Harrison & Lyne 1993).

The largest sample of scintillation speeds contains 71 pulsars and has been collected by Cordes (1986). Recent proper motion measurements using MERLIN on a sample of 44 pulsars (Harrison, Lyne & Anderson 1993) have permitted a reassessment of the method (Harrison & Lyne 1993). There are clear systematic differences between the two methods of velocity determination. In particular, Harrison & Lyne (1993) showed that the values of V_{iss} are smaller than V_{pm} by about a factor of approximately 2 (Figure 1). Moreover, they found that the discrepancy was even greater for pulsars at large z-height from the galactic plane and smaller for those at small z-height. They noted that if most of the scattering occurs in a screen close to the Earth, then there will be a leverage effect, and the pattern speed will be less than the pulsar speed. It seems clear that the scintillation velocities were previously systematically underestimated because of a concentration of scattering material close to the Galactic plane with a scale-height of less than 100 pc. Once the velocities have been corrected for such systematic effects (Harrison & Lyne 1993), it is still found that the scintillation speeds differ from the proper motion ones by up to a factor of 2 in either direction in individual cases. These differences must be due to unmodelled variations in the position of scattering material along the line of sight and, to a lesser extent, due to errors in the distance which enters the velocity ratio as the square root.

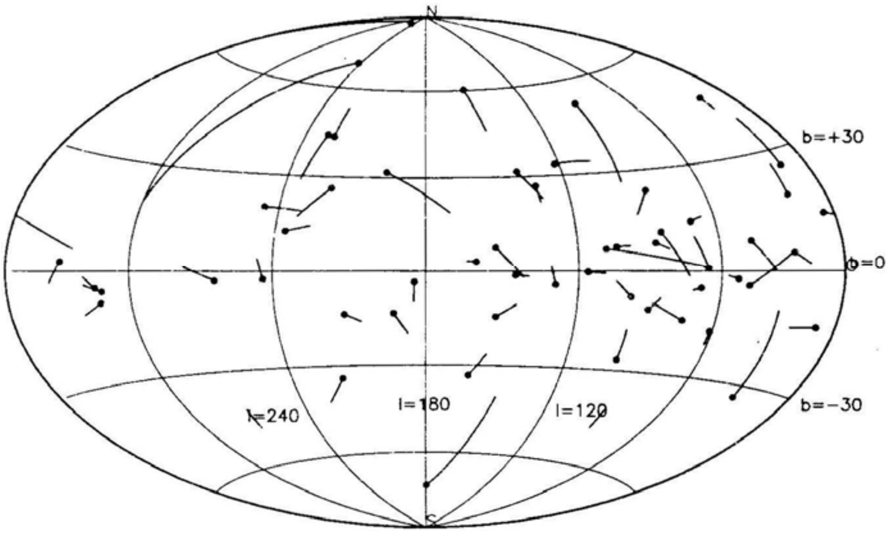

Figure 2: The galactic distribution of pulsars and their velocity vectors. The tails represent the approximate paths.travelled during the last million years (After Harrison, Lyne & Anderson 1993).

3. Pulsar Birth Velocities

The velocity vectors obtained from proper motion measurements are shown in figure 2 and demonstate a general migration from the galactic plane. These are mostly consistent with pulsar birth in a progenitor, population I, layer close to the plane, from which their velocities subsequently carry them away. Most of the pulsars which appear to be moving towards it are still within the progenitor layer, while some others at high latitude may in fact be moving away from the galactic plane if they have a reasonable value of radial velocity. However, there are about 4 pulsars which are at large *Z* distance and are undoubtedly moving towards the plane (Harrison, Lyne & Anderson 1993). These objects may have their origin in the massive OB runaway stars.

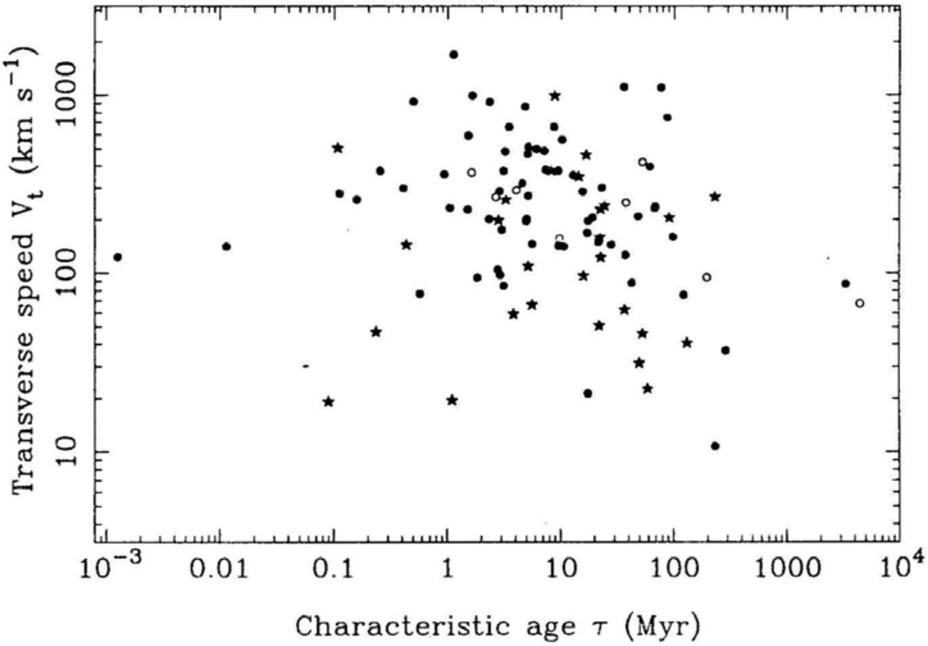

Figure 3: The transverse speed V_t of 99 pulsars plotted against characteristic age $\tau = P/2\dot{P}$, where P and $\dot{P}$ are the pulsar rotation period and time derivative. Pulsars with only upper limits to their transverse speed are represented by open circles at half the upper limits. Starred symbols represent transverse speeds obtained from scintillation data. The mean transverse speed for the 29 pulsars younger than 3 Myr is 345 km s^{-1}. In the unlikely circumstance that the two young pulsars in this group with upper limits have zero speed, this value would only be reduced by 6%.

Lyne & Lorimer (1994) have recently reassessed the velocities of normal, solitary pulsars and have used the 87 velocities derived from the proper motion data, apart from PSR B0736–40 which lies behind the Gum nebula and has an unknown distance in excess of 0.5 kpc. The distances *D* required to calculate the velocities were obtained from the new electron density model of Taylor and Cordes (1993) which is based upon a number of new independent distance measurements and which clearly shows that previous models had underestimated the distance to nearby pulsars. Because of the imprecision of the scintillation velocities, Lyne and Lorimer (1994) relied where possible upon the more direct proper motion measurements. However, for 14 pulsars which only have upper limits to their proper motion and a further 13 which do not have proper motion data, the scintillation data (Cordes 1986; Fruchter 1988) were used to estimate V_t. These scintillation speeds have been calculated using the new distance model (Taylor & Cordes 1993) and the appropriate correction for the medium localisation (Harrison & Lyne 1993). Thus the sample contains 99 pulsars, of which only 8 have upper limits to V_t.

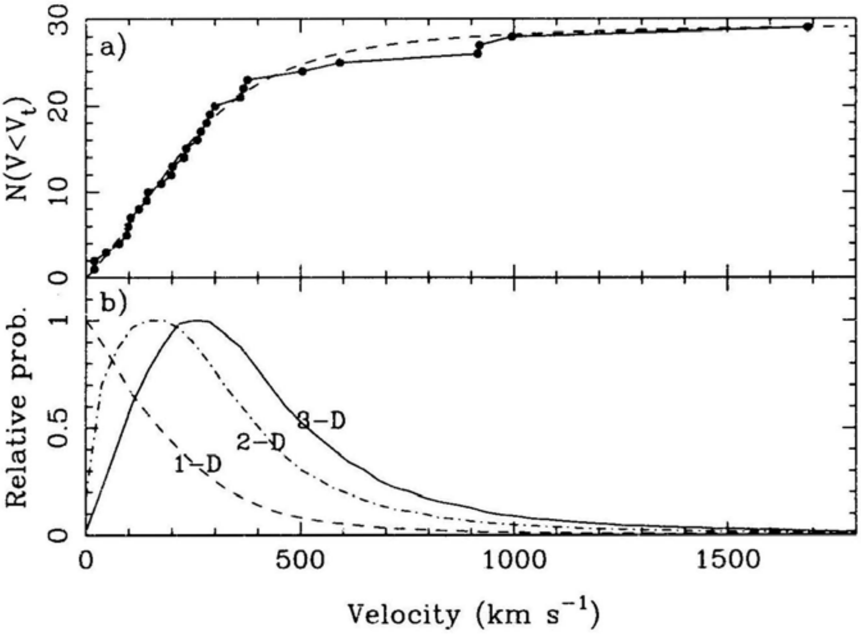

Figure 4: a) The cumulative distribution of transverse speeds V_t for the 29 pulsars younger than 3 Myr. For these pulsars, the selection effect against detecting high velocity pulsars is negligible and this is a good representation of the 2-D speed distribution at birth. The dashed curve is an analytic approximation to the data having the same mean and r.m.s. (see text), b) The 1-D, 2-D and 3-D velocity distributions corresponding to the analytic function in (a), obtained using an iterative Monte Carlo simulation. The 3-D distribution shows that pulsars have a mean space velocity of about 450 kms $^{-1}$.

This sample has a mean V_t of 300 ± 30 km s $^{-1}$, compared with 134 km s^{-1} obtained 12 years ago from 26 measurements (Lyne, Anderson & Salter 1982). The increase in value reflects the change in the adopted distance scale (Taylor & Cordes 1993), and also the greater number of young and higher velocity pulsars observed in the recent astrometric surveys (Harrison, Lyne & Anderson 1993; Bailes et al 1989; Fomalont et al. 1992). The much improved statistics also show that this velocity is not representative of the velocities at birth since we see that young pulsars on average have higher velocities than older ones (Harrison, Lyne & Anderson 1993). This can be seen in Fig. 1 in which the transverse speed of pulsars is plotted against characteristic age and surely does not arise because pulsars slow down significantly as they age. Rather, it is due primarily to a selection effect, first recognised by Cordes (1986): young pulsars are born from Population I stars, close to the galactic plane, and those pulsars with high velocity mostly move rapidly away from the plane (1000 km s^{-1} ≈ 1 kpc Myr^{-1}). After about 10 Myr, the mean distance of the fastest pulsars from an observer on the galactic plane is significantly greater compared with their mean distance at birth, reducing their likelihood of detection and hence lowering the apparent mean velocity. By this time, the pulsars remaining within detectable range are those with small velocity and a few high velocity ones moving roughly parallel to or towards the plane of the Galaxy (Harrison, Lyne & Anderson 1993).

During the first 3 million years, the strength of the above selection effect is minimal and the observed transverse speed distribution of the 29 pulsars younger than this should be a good representation of the true V_t distribution at birth. This distribution has a mean of 345 ± 70 km s^{-1} and an r.m.s. of 499 km s^{-1}. The mean velocity of only 105 ± 25 km s^{-1} for the 10 oldest pulsars illustrates the strength of the effect.

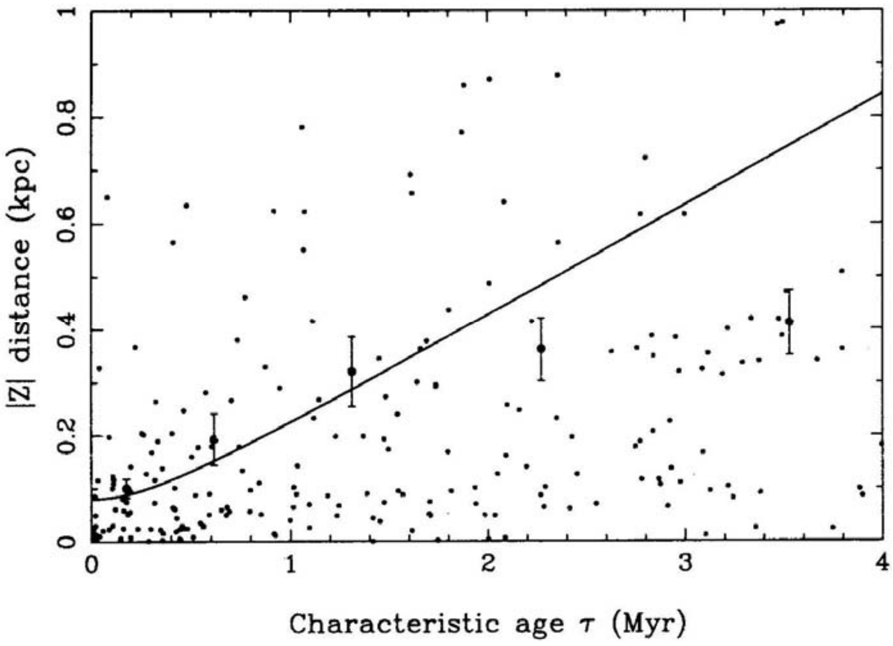

Figure 5: The distance of pulsars from the galactic plane |*Z*| shown as a function of characteristic age τ for all the pulsars detected in the major pulsar surveye. The large symbols represent the means of groups of 40 pulsars. The line shows the variation expected from a simple dynamical model with the mean velocity derived from Fig. 4.

The 3-D space velocities must of course be somewhat greater than the observed 2-D transverse velocities, and we can estimate them statistically if we make the reasonable assumption that the velocities at birth are isotropic. Lyne & Lorimer (1994) used a simple, iterative Monte Carlo technique to determine the 1-D and 3-D velocity distributions required to give the observed 2-D transverse distribution. A cumulative plot of this observed distribution is compared with the model one in Fig. 4a and the derived distributions are shown in Fig. 4b. From the 3-D distribution, it seems that the space velocity of pulsars at birth has a mean of 450 ± 90 km s^{-1} and an r.m.s. value of 535 km s^{-1}. This mean space velocity is a factor of three higher than the value of ~ 150 km s^{-1} deduced from the earlier sample (Lyne, Anderson & Salter 1982). The increase arises from the 3 main factors described above; namely a younger, faster sample (× 1.4), the new distance model (× 1.6) and the selection effect (× l.2).

There are two other indications that the birth velocities are large: firstly, such high birth velocities will give rise to a rapid migration from the galactic plane with a mean velocity V_z equal to 210 km s^{-1}, the mean of the 1-D distribution in Fig. 4b. This is clearly seen for the whole observed pulsar population in Fig. 5 as an increase in the mean distance Z of pulsars from the galactic plane with age. Assuming that pulsars are born in a progenitor Population I distribution with a width in Z of 80 pc, then pulsars of age τ will have a mean height given approximately by $Z = \sqrt{Z_0^2 + V_Z^2\tau^2}$. This function is also shown in Fig. 5 and describes the data well for ages below about 2 Myr, confirming the large velocity dispersion. For older pulsars, the selection effect described earlier reduces the detected number of large Z pulsars and hence the mean Z of the observed population.

Secondly, the high transverse velocities found here are close to estimates of the velocities of young pulsars required by associations of pulsars with supernova remnants (Caraveo 1993). These associations are usually made on the basis of similarity of age, distance and position on the sky. Often the pulsar has moved significantly from the centre of the remnant since the supernova explosion, and the pulsar velocity can be determined from the ratio of the separation and the age. Taking 13 reasonably convincing associations, we find that the mean transverse pulsar velocity is about 530 ±180 km s^{-1}. Using the same form of velocity distribution as above, this implies a mean space velocity of 690 ± 230 km s^{-1}.

4. The Velocities of Binary and Millisecond and pulsars

The velocities of a handful of millisecond pulsars have been measured, mostly from measurements of proper motion from timing observations, made possible by the high rotational stability of these objects (e.g. Kaspi, Taylor & Ryba 1994; Bell et al. 1994; Nice & Taylor 1995). Some estimates have been made from scintillation measurements (e.g. Nicastro & Johnston 1995). The corresponding transverse velocities of these objects are almost without exception less than 100km s^{-1}, This is not surprising, as the large ages of such pulsars will result in any higher velocity ones occupying a much greater scale height above the galactic plane, making them more difficult to detect. In fact, a birth velocity distribution with a mean of 80 km s^{-1} or greater seems to be required to explain the wide observed Z distribution (Lorimer 1995). They probably do have much smaller velocities than normal pulsars since they have, or are believed to have had, stellar companions at some time since their formation. It seems likely that these objects represent the minority of neutron stars which were formed in binary systems with small velocity kicks, those with large velocities being disrupted. The binary systems which did survive the formation event will also be somewhat more massive than a single neutron star, because of the presence of the companion, so reducing the systemic velocity kick even further.

5. Discussion

It is now clear that most pulsars are born with velocities of around 400-500 km s^{-1}. These large values indicate that their origin must lie in the kinetics of asymmetric supernova collapse rather than the disruption of binary systems (Dewey & Cordes 1987; Bailes 1989). The kinetic energy of the neutron stars so formed are an order of magnitude greater than previously thought. Although the mechanisms of such collapse are not well understood, the high degree of asymmetry now required might also be expected to show corresponding asymmetry in the gaseous supernova remnant in the opposite direction to the pulsar velocity.

While most recent statistical studies of the pulsar population and its evolution (Narayan & Ostriker 1990; Bhattacharya et al. 1992; Lorimer et al. 1993) have taken account of the spatial separation of fast and slow pulsars, this effect has been underestimated by a factor of 3 and they will need to be repeated. Similarly, the increase in birth velocity will clearly have a major effect upon our understanding of the number of pulsars that remain bound in binary systems, globular clusters and the Galaxy. While such high velocities make it easier to understand the small number of pulsars in binary systems (Bhattacharya & van den Heuvel 1991), the small proportion (~ 0.7%) with velocities below about 50 km s^{-1} make the large population of neutron stars in globular clusters surprising unless they are formed in a less violent scenario such as accretion induced collapse of a white dwarf (Bailyn & Grindlay 1990).

With mean birth velocities of 450 km s^{-1}, more than half of all pulsars will escape the galactic gravitational potential. Those that remain bound will form a much larger spherical halo of old neutron stars than previous models suggested (Paczy'nski 1990; Frei, Huang & Paczy'nski 1992; Blaes & Madau 1993). Such a distribution will more nearly match that required to produce the isotropic distribution of gamma-ray bursts observed by the Burst and Transient Source Experiment (Meegan et al. 1992). This provides some support for the possibility that old, high velocity pulsars are the source of the bursts (Hartmann, Epstein & Woosley 1990; Li & Dermer 1992), although it seems that only the high velocity tail of the distribution could provide a population of sufficient isotropy.

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