Part 1
The Pulsar Population

Section B
Population Studies

https://doi.org/10.1017/S0252921100040963 Published online by Cambridge University Press

Pulsars : Problems & Progress
ASP Conference Series, Vol. 105, 1996
S. Johnston, M. A. Walker and M. Bailes, eds.

Pulsar Velocities – Revisions & Ramifications

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Abstract. The recent shift of opinion concerning the distribution of pulsar velocities at birth with a mean value of 400–500 km/s has several ramifications for our understanding of the origin and evolution of pulsars. From the present data, there is no convincing evidence for a causal correlation between velocity and magnetic field, any magnetic field evolution in neutron stars or that galactic neutron stars once active as radio pulsars are the sources of γ-ray bursts. Asymmetric kicks seem the most plausible origin for the high velocities.

1. Historical Introduction

Pulsars have long been known to have space velocities about an order of magnitude greater than those of their likely progenitors: the O and B stars which have systemic velocities typically in the range 10–50 km/s. Direct evidence first came from the proper motion measurement of the Crab pulsar (Trimble 1968) implying a velocity $\gtrsim$ 100 km/s. Further evidence came from studies of galactic distribution of pulsars (Gunn & Ostriker 1970) which soon established that their scale–height is large ($\sim$ 400 pc) requiring a larger velocity dispersion compared to normal stars which have a scale–height $\sim$ 50 pc. In addition, one can estimate the proper motion required to satisfy any association between a young pulsar and a supernova remnant (Kaspi, these proceedings). To accurately assess the velocity distribution of pulsars at birth, however, a well defined sample of pulsar proper motion *measurements* is desirable. By the mid 1980s, about 30 such measurements were available; largely due to interferometric techniques (Lyne, Anderson & Salter 1982) but also from pulse time-of-arrival analyses (Downs & Reichley 1983) and scintillation measurements (Lyne & Smith 1982).

There are three main theories which attempt to explain the origin of pulsar velocities. After Radhakrishnan (1992) I shall classify these as either pre–natal, natal or post–natal theories depending on *when* the neutron star acquired its velocity. In the pre–natal category, it is assumed that most neutron star progenitors are members of binary systems. The more massive star in the system (the primary) evolves off the main sequence before its less massive companion (the secondary), ultimately undergoing a supernova explosion which forms the neutron star. If more than half the total mass is ejected from the binary sys-

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tem during the explosion, the binary disrupts leaving both stars moving away at speeds comparable to their pre-supernova orbital velocities. This scenario can produce relatively high velocity ($\sim$ 150 km/s) solitary neutron stars (Gott, Gunn & Ostriker 1970) and the so-called "OB runaways" (Blaauw 1961). In the natal category, the pulsar receives a randomly oriented "kick" at birth due to conservation of linear momentum in a slightly asymmetric supernova explosion (Shklovskii 1970). Even relatively small asymmetries in the collapsing envelope can produce kicks as large as 1000 km/s – sufficient to unbind systems in which less than half the pre-supernova mass is ejected. Finally, in the post-natal category the pulsar is considered to be an oblique rotator. Asymmetry between the dipole and quadrupole moments creates a radiation reaction torque which accelerates the newly born star along the direction of its magnetic axis soon after birth – the "rocket" theory (Harrison & Tademaru 1975).

The lack of any observed correlation between the direction of pulsar proper motion vectors and their magnetic inclination angles (Anderson & Lyne 1983) has virtually ruled out the rocket theory. Since hydrodynamical simulations of stellar collapse to produce large asymmetric kicks are still somewhat uncertain (see Iben & Tutukov 1996 and refs therein), the most commonly accepted origin for pulsar velocities was the binary break-up model with perhaps a modest kick of order $\sim$ 90 km/s (Dewey & Cordes 1987).

2. Reasons to Revise

There is now a large body of evidence for a much broader velocity spectrum that extends out to $\gtrsim$ 1000 km/s. Lyne & Lorimer (1994) identified three key reasons for a fresh look at the birth velocities:

(*i*): During the 1980s, a number of interferometric proper motion surveys were undertaken (Bailes et al. 1990; Formalont et al. 1992; Harrison, Lyne & Anderson 1993). Together with a large scintillation study by Cordes (1986) the number of pulsars for which the transverse speed can be calculated has risen by a factor of 3. Many of these pulsars are younger ($\lesssim 10^{6.5}$ yr) and more distant than those in the earlier sample which was primarily sensitive only to older ($\gtrsim 10^7$ yr) low-luminosity pulsars in the solar neighbourhood.

(*ii*): The pulsar distance scale has been significantly modified (Taylor & Cordes 1993; Weisberg, these proceedings) so that many of the distance estimates to pulsars with kinematic data have been upwardly revised by an average factor of 2. This, of course, systematically increases the transverse speeds obtained from proper motion data by the same factor, whilst transverse speeds from scintillation data rise as the square root of the distance.

(*iii*): There is a simple selection effect pointed out by several authors (Anderson & Lyne 1983; Cordes 1986; Caraveo 1993; Lyne & Lorimer 1994; Frail, Goss & Whiteoak 1994) *viz* young, high velocity pulsars travel further from their birth places in a given time than those born with lower velocities. Thus in a proper motion sample, which is largely flux limited, the mean velocity of pulsars more than a few million years old will be underestimated simply because the higher velocity pulsars become too distant and therefore too weak to be detectable.

Taking these factors into consideration, Lyne & Lorimer (1994) found that the mean speed of pulsars at birth must be $\sim$ 450 km/s, a factor of 3 higher than the previously "accepted" value of 150 km/s. A similar value was obtained by Frail et al. (1994) based on, somewhat less certain, transverse speeds derived from pulsar–supernova remnant associations.

3. Ramifications

3.1. The demise of the velocity–magnetic field correlation

An intriguing aspect of the velocity data over the years has been the apparent relationship between the transverse speed and the inferred magnetic field strength (Harrison & Tademaru 1975; Anderson & Lyne 1983). In the so–called "V–B correlation", pulsars with higher magnetic fields appear to possess, on average, larger space velocities than those pulsars with weaker magnetic fields. The correlation was recently reassessed by Lorimer, Lyne & Anderson (1995) using the latest data. From Fig. 1 of their paper, it can be immediately seen that any "correlation" is much less apparent with a large scatter of transverse speeds, particularly at large magnetic fields.

Computer simulations (Lorimer 1994; Itoh & Hiraki 1994; Itoh, Kotouda & Hiraki 1995) demonstrate that such a scatter diagram is consistent with models of the pulsar population in which *no intrinsic V–B correlation* has been assumed. Indeed, if the correlation was truly causal, then it should be most apparent at in the youngest pulsars which are less affected by the spatial separation selection effect. No significant correlation is seen amongst the 30 youngest pulsars in the sample (Lorimer et al. 1995). This removes much of the justification for invoking *ad hoc* V–B correlations at birth and dual population models to explain the observations (Narayan & Ostriker 1990).

3.2. Magnetic field evolution

By the mid 1980's, the idea that magnetic fields decay on a $1/e$ folding time of $\lesssim$ 10 Myr had been virtually enshrined in the literature for over a decade (see *e.g.* Gunn & Ostriker 1970; Lyne, Anderson & Salter 1982; Lyne, Manchester & Taylor 1985). Much of the justification rested on a novel interpretation of a sample of 26 proper motion measurements by Lyne et al. (1982; see also the contribution by Camilo in these proceedings). The authors plotted kinetic ages τ_k (inferred from proper motion perpendicular to the galactic plane) which are largely model independent against characteristic ages τ_c (inferred from rate of pulsar spin-down) which depend upon the magnetic field decay time–scale. Assuming τ_k is a good approximation to the true age, for exponential decay with a time constant t_D it is straightforward to show that

$$\tau_k = \frac{t_D}{2} \ln \left(1 + \frac{2\tau_c}{t_D} \right). \tag{1}$$

Lyne et al. found the kinetic ages were systematically lower than characteristic ages for many of the pulsars in their sample. Using equation (1), they resolved the discrepancy by invoking magnetic field decay on time–scales $\lesssim$ 10 Myr.

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This approach was however called into question by Bailes (1989) on the basis that errors associated with the kinetic ages (due to the unknown birth place of the pulsar) are too large to conclude for or against field decay. In fact, population syntheses (Lorimer 1994) show that the kinetic age–characteristic age diagram is completely insensitive to the assumed field decay time-scale. This can be seen clearly in Fig. 1 which shows two such diagrams displaying the same behaviour despite a factor of 10 difference in the assumed model field decay time.

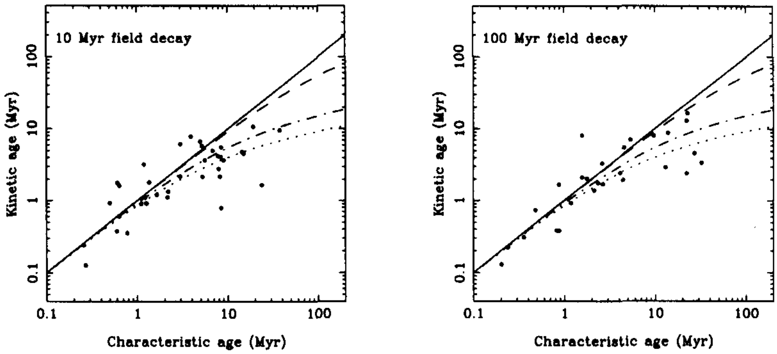

Figure 1. Kinetic age–characteristic age diagrams for a model population with a field decay time of 10 Myr (left panel) and a decay time of 100 Myr (right panel). The lines represent evolutionary tracks followed by pulsars in the absence of field decay (solid line), and using equation (1) for field decay times of 100 Myr (dashed), 10 Myr (dashed/dotted) and 5 Myr (dotted). Taken from Lorimer (1994).

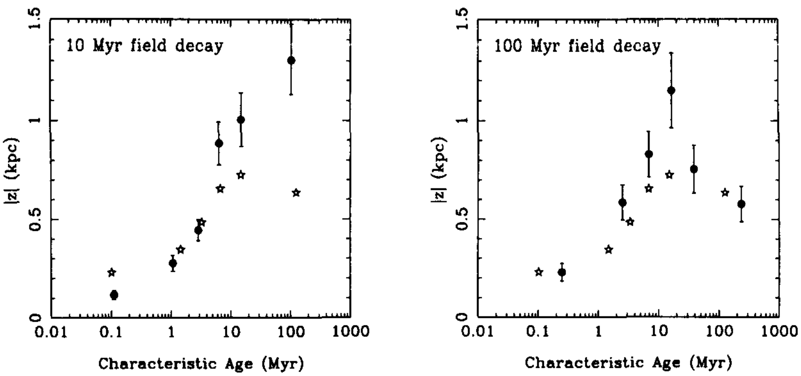

Figure 2. Binned Z–T diagrams comparing a model with a 10 Myr field decay time-scale (left panel) against a model assuming a 100 Myr time-scale (right panel). In both cases, the observed sample is represented by the starred symbols, whereas the filled symbols represent the model pulsars. The error bars are statistical estimates (Lorimer 1994).

One resolution to the problem is to look at the "Z–T" diagram, where Z is the absolute value of the distance from the galactic plane and T is the characteristic age. Fig. 2 shows model Z–T diagrams for synthetic pulsar populations

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generated assuming a mean birth velocity of $\sim$ 450 km/s and magnetic field decay time–scales of 10 and 100 Myr. In both cases, the model samples agree reasonably well with the observed sample below characteristic ages of about 20 Myr. The most prominent feature in Fig. 2 is the bin with a characteristic age of $\sim$ 100 Myr; here, the 10 Myr decay model strongly diverges from the observed data whilst the 100 Myr model is in better agreement with the data.

The reason for this divergence can be explained in terms of the different magnetic decay time-scales and therefore in the true ages of pulsars in the models: In the 10 Myr decay model, it is straight–forward to show using equation (1) that a pulsar with a characteristic age of 100 Myr has a true age of only $\sim$ 15 Myr. Given the high birth velocities required to explain the velocity distribution, even in 15 Myr, typical pulsars can reach z heights of well over 1 kpc in that time and still be luminous enough to be detected by the pulsar surveys. In the 100 Myr decay model however, from equation (1), a decay time–scale of 100 Myr implies that a pulsar with a characteristic age of 100 Myr is in fact about 55 Myr old. Any pulsar born with a z component of velocity $\gtrsim$ 200 km/s can easily reach a sufficient z height in 55 Myr to evade detection. This leaves only the old, low velocity pulsars residing at much lower z heights, consistent with the observed data. Since this fact applies to decay times $\gtrsim$ 100 Myr, our results suggest that there may be *no need* to have any field decay in order to explain the Z–T diagram. Similar conclusions, from population syntheses, have been reached by (Bhattacharya et al. 1992; Wakatsuki et al. 1992; Itoh & Hiraki 1994; Itoh, Kotouda & Hiraki 1995).

3.3. Old neutron stars as the γ–ray burst sources?

Models of the distribution of old neutron stars (*e.g.* Paczyński 1990) were consistent with the observed distribution of γ–ray bursts (GRBs) prior to 1990 providing that the detector sampling distances were $\lesssim$ 1–2 kpc. An obvious prediction from the galactic neutron star model is that the improved sensitivity, and therefore sampling distance, to GRBs with the Burst and Transient Source Experiment (BATSE) on–board the *Compton Gamma–Ray Observatory*, would show a concentration of bursts towards the galactic centre. However, the continued isotropic distribution of bursts observed by BATSE and the deficit of weak events (Meegan et al. 1992) raised serious doubts on the likelihood of the galactic neutron star theory and in favour of a cosmological origin.

Following the revision in pulsar birth velocities, one expects the distribution of old neutron stars to be more isotropic than previously supposed and possibly consistent with the burst isotropy observed by BATSE. However, even with the Lyne–Lorimer velocity distribution, the expected distribution of old ($\gtrsim 10^8$ yr) neutron stars can be shown to be strongly anisotropic with a significant fraction of the lower velocity neutron stars being closely bound to the galactic centre (Lorimer 1994; Podsiadlowski, Rees & Ruderman 1995). As pointed out by the above authors, if only the subset of neutron stars born with velocities above about 600 km/s would emit bursts, then their distribution would be isotropic and consistent with the BATSE data. This is simply because, regardless of initial location, they escape the galactic gravitational potential after $\sim 10^{7.5}$ yr.

If galactic neutron stars are the sources of GRBs, why should only high–velocity ones produce the bursts? Li & Dermer (1992) proposed, on the basis of the V–B correlation, the highest velocity pulsars also have the largest magnetic fields. Given the complete lack of evidence in favour of a V–B correlation, this does not seem at all plausible. If the low and high velocity neutron stars are significantly different, one might expect them to show other differences, for example in pulse profile morphology. No such distinction is supported by the vast body of pulse profile data, which show no significant difference in the fraction of high and low velocity pulsars with multiple components or interpulses. In summary, the lack of any firm evidence to suggest that pulsars born with high velocities will become GRB sources in favour over those born with lower velocities leads us to conclude that *relic neutron stars from the radio pulsar population* are not the sources of γ–ray bursts. More recently Hartmann & Narayan (1996) demonstrated this from simple energetic arguments.

In an interesting Ap J. *Letter*, Duncan & Thompson (1992) propose another class of neutron stars. Known as "magnetars", their typical magnetic fields are predicted to be $\sim 10^{15}$ G. With such large magnetic fields, magnetars spin down to periods ~ 10 s within 1000 yr and are relatively short lived as potential radio pulsars. The authors outline a number of mechanisms in which the large magnetic fields induce velocities ~ 1000 km/s. From the above discussion, such high velocities are in principle more than sufficient to mimic the isotropic distribution observed in the BATSE data. However, from the energy–loss arguments presented by Hartmann & Narayan (1996), magnetars lose their rotational kinetic energy well within the "turn on time" of $\sim 10^{7.5}$ yr required to guarantee isotropy. Duncan & Thompson (1992) point out that the 8 s periodicity observed in the soft γ–ray repeater 0525–66 in the LMC is consistent with a young rotating neutron star with a 6×10^{14} G field. The detection of an extremely long period radio pulsar in a soft γ–ray repeating source (or anywhere else in the Galaxy for that matter!) would obviously be of great interest.

4. The high velocity tail

A quick glance at the latest proper motion and scintillation data suggest that the space velocities of nine pulsars exceed 1000 km/s. Perhaps the most famous example is PSR B2224+65 which is responsible for the H–α bow shock emission in the Guitar Nebula (Cordes, Romani & Lundgren 1993; also see the contribution by Cordes in these proceedings). In addition to many of the claimed supernova remnant associations, the neutron star–soft γ ray repeater connection also requires velocities ~ 1000 km/s (*e.g.* Kulkarni et al 1994). Whilst I cannot vouch for *all* of the above results, particularly those in which velocities are inferred, even the most sceptical of sceptics would struggle to dismiss such a large body of evidence in favour of an extended velocity spectrum.

So what do the latest results tell us about the origin of pulsar velocities? As Radhakrishnan (1992) and others have pointed out, the mere presence of these high velocity pulsars are perhaps the most compelling arguments that some sort of kick has been imparted to the neutron star at or during birth. This view is not universally held, however, and in a recent paper Iben & Tutukov (1996) dispute this view and advocate that the high velocity pulsars can be produced in an evolutionary model assuming symmetric supernova explosions in massive binaries in which the system disrupts after the second explosion. An important prediction of their model, however, is that such pulsars are vastly outnumbered by low velocity $\lesssim$ 50 km/s pulsars produced from the disruption of wide, low–mass binaries. In their distribution, there are as many neutron stars produced with velocities below 20 km/s as there are above it.

In an attempt to test the validity of this prediction, Iben & Tutukov compare their theoretical velocity spectrum with the sample of pulsars with measured proper motions and distances *less than* 500 pc. The authors claim that this sample of nearby pulsars better reflects the underlying distribution of low–velocity pulsars which are more difficult to measure accurately at larger distances than high velocity pulsars. Whilst it is true that high velocity pulsars are easier to measure than low velocity ones, I would argue, as Dewey & Cordes (1986) have done previously, that the sample of pulsars in the solar neighbourhood contains *only* old, low velocity objects.

5. Millisecond Pulsar Velocities

Millisecond pulsars, often referred to colloquially as "fast pulsars", are rather slow kinematically by comparison with the normal pulsars. Presently, there are about 10 reliable proper motion measurements from high–precision timing experiments which suggest a mean space velocity for these objects of $\sim$ 100 km/s. This lower velocity is to be expected for two reasons. Firstly, because millisecond pulsars have typical characteristic ages $\sim$ a few Gyr, those with the highest velocities will be further from the Sun and therefore harder to detect. Secondly, if we believe that the genesis of these objects is intimately linked to a binary origin, only those binary systems with generally smaller kick velocities will survive. Population syntheses by Bhattacharya (these proceedings) show that the observed millisecond pulsar velocities are generally consistent with the low end of the normal pulsar velocity spectrum. For a detailed discussion on the origin of binary millisecond pulsar velocities see Tauris & Bailes (1996). The origin of the velocities of single millisecond pulsars remains poorly understood.

6. Conclusions & Future Prospects

Perhaps the most fundamental issue in this area is the distribution of pulsar velocities at birth. Currently, I am aware of four proposed forms: Lyne & Lorimer (1994), Iben & Tutukov (1996); Phinney & Hansen (in preparation) & Cordes et al. (in preparation). As Bhattacharya and Hartmann et al (these proceedings) demonstrate, it is not immediately obvious which distribution correctly describes the data. From an observational point of view, I think that progress can be made from the following areas: more proper motion measurements of young pulsars, deep radio searches for young pulsars associated with supernova remnants and further optical searches for bow–shock nebulae. Theoretically, further population syntheses are clearly worthwhile, with particular emphasis on isolating key causes of observed phenomena, and testing the validity of techniques applied to the observed velocity sample to make inferences on its underlying appearance. Given the requirement for large natal kicks, further theoretical developments in understanding the kinetics of supernova explosions would be of great interest.

https://doi.org/10.1017/S0252921100040963 Published online by Cambridge University Press

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