Energetic Young Radio Pulsars

J. F. Bell¹

ABSTRACT

Young radio pulsars shed vast amounts of rotational energy, sometimes as high as 100,000 times the total energy loss rate from the sun. The wide range of phenomena resulting from this energy loss include: glitches, timing noise, jets, bow shocks, bullets and plerions and are be reviewed from an observational perspective. Past and proposed surveys for young radio pulsars are summarised along with pulsar birth velocities and associations with supernova remnants. There are now 4 radio pulsars with measured braking indices. The resulting constraints on the evolution of young radio pulsars are discussed in light of the presently observed population of pulsars. Observations at optical, X-ray and gamma ray energies which provide a unique opportunity to study the emission and magnetospheric processes are described briefly. The status of pulsar birth velocities and supernova remnant associations are summarised.

1. Introduction

This review summarises the wide range of phenomena that occur in, or are associated with, energetic young radio pulsars. The scope is confined to rotation powered radio pulsars as accretion powered pulsars are discussed by others at this meeting. The level is introductory, providing the background for other speakers who discuss particular aspects in more detail. From here on rotation powered radio pulsars are referred to as pulsars and energetic young rotation powered radio pulsars are referred to as young pulsars. As a working definition we consider a pulsar with a characteristic age less than 100,000 years to be young. A key point to be emphasised is that many phenomena associated with young pulsars arise from the very high spin down energies that they deposit in their surroundings.

The layout of this review is as follows:

- Basic properties of young pulsars
- Surveys for young radio pulsars
- Glitches, timing noise and braking indices
- High energy observations
- Interstellar medium interactions
- Birth velocities
- Associations with supernova remnants

2. Basic Properties of Young Pulsars

The age of a pulsar with period $P$ and period derivative $\dot{P}$, is given by

$$t = \frac{P}{(n-1)\dot{P}} \left(1 - \left(\frac{P_0}{P}\right)^{(n-1)}\right)$$

(1)

where $P_0$ is the rotation period at birth and $n$ is the braking index. $P_0$ can only be determined in a couple of special cases and it is generally assumed that $P_0 \ll P$. It is further assumed that magnetic dipole braking is the dominant braking force, for which $n = 3$. Applying these assumptions to (1) gives the characteristic age $t_c = P/2\dot{P}$. Lines of constant characteristic age are shown in Figure 1 and suggest that most pulsars are $10^6 - 10^7$ years old. In the middle at the top of Figure 1 many of the young pulsars are shown with starred symbols which indicate that they are possibly associated with supernova remnants (SNRs).

The median values of a range of pulsar parameters are compared in Table 1 for three populations of pulsars: young, normal and millisecond pulsars (MSPs). The most noticeable unique features of young pulsars are the large spin down energies ($\dot{E}$) and their small distance ($z$) from the galactic plane. This very low height above the galactic plane is striking (Figure 2). They also appear to have slightly larger magnetic fields ($B$), dispersion measures (DM) (and therefore distances, as shown in Figure 3) and Luminosities ($L$). However as can be seen in Figure 4 the scatter in the luminosities is large for the young pulsars,
while the MSPs are more tightly clustered. The high spin down energies of both these population relative to the main population is also very clear in Figure 3. Rather surprisingly the observed young population is now smaller than the observed MSP population.

The group of presently known young pulsars ($t < 100,000$ years) are listed in Table 2 along with several of their important properties which are summarised in column eight. There are three very young pulsars with ages just over 1000 years, PSRs B0531+21 (Crab) and B1509–58 in the Galaxy and PSR B0540–69 which is one of the four known pulsars in the large Magellanic cloud. PSR J0633+1746 (Geminga) is included in the list due to its similarity to radio pulsars, even though it has not been detected at radio wavelengths.

3. Surveys for Young Radio Pulsars

3.1. Selection Effects

Most pulsars are born in or near the Galactic plane where the progenitor population is located. Since most young pulsars will not have had time to move very far from the Galactic plane they too are found most abundantly in the Galactic plane (Figure 3). This has important implications for surveys for young pulsars, including some severe selection effects. We begin by discussing those which broaden the pulse profile. The importance of this can be seen from the fact that the sensitivity of a pulsar survey depends on the square root of the observed duty cycle of the pulsars it seeks to find (Johnston et al. 1992). That is, a large duty cycle leads to a poorer sensitivity.

Dispersion smearing across individual frequency channels (Bhattacharya, these proceedings) can be significant. For example, in the recent Parkes survey (Manchester et al. 1996, Lyne et al. 1997) the dispersion smearing of a pulsar with a dispersion measure of $DM = 1000$ cm$^{-3}$pc would be 12.8 ms. This smearing is strongly frequency dependent and is given by

$$\Delta t = \left(\frac{204}{f}\right)^3 DM \text{ } ms/MHz$$

Fig. 1.— $P$-$\dot{P}$ diagram for radio pulsars. Circles indicate pulsars in circular orbits, ellipses indicate pulsars in eccentric orbits and stars indicate pulsars associated with supernova remnants.

Fig. 2.— An Aitoff projection of the Galactic pulsar population. Young pulsars are shown with large dots.
Fig. 3.— A face-on view of the Galactic pulsar population. Young pulsars are shown with large dots.

where $f$ is the radio frequency at which the observations are made. If a frequency a factor of 3 higher is used, then dispersion smearing is reduced by a factor of 27 and the sensitivity potentially improved by a factor of 5! This problem could also be overcome by using much narrower frequency channels, but the smearing caused by interstellar scattering cannot (Bhattacharya, these proceedings). Here the pulse broadening depends on $f^{-4}$, again suggesting that typical survey frequencies of $\sim 400$ MHz are not optimal for finding young pulsars. As young pulsars are relatively luminous, they may be found at large distances if the increased dispersion smearing and scattering can be countered by observing at high frequencies.

The frequency dependence of the sky background and the spectral indices of pulsars are also important to consider when designing a survey. The sky background temperature close to the Galactic plane can be as high as 400 K at 400 MHz, completely dominating the receiver noise. However, between 400 and 1500 MHz the sky background has a frequency dependence of $f^{-2.6}$, resulting in a background temperature of $\sim 20$ K at 1400 MHz, comparable to a well optimised receiver. The flux detected from young pulsars typically depends on $f^{-2}$ for frequencies between 400 and 1500 MHz. While this means that the observed fluxes are smaller at higher frequencies, the dependence on frequency is flatter than the dependence for dispersion smearing, scattering and the sky background.

3.2. Past, Present and Future Surveys

A moderately high frequency search provides an optimal approach for finding young pulsars. Such searches have already been undertaken (Johnston et al. 1992, Clifton et al. 1992) and were very successful. They found a sample of 86 pulsars in a region of sky that had already been well searched at lower frequencies. The mean age of this sample is 10% of the mean age of the entire pulsar population. These two surveys are summarised together with three next generation high frequency surveys for young pulsars.
in Table 3. The Nancay survey is a collaboration between Meudon, Berkeley and Naval Research Labs. and will provide excellent sensitivity to young pulsars, with vastly improved time and frequency resolution and limiting sensitivity.

One of the difficulties of high frequency surveys is the slower sky coverage due to the smaller beam. For example a 1400 MHz survey would take 12 times as long as a 400 MHz survey to cover a given region with the same integration time and would collect substantially more data. At Parkes and Jodrell Bank, a novel approach of using many simultaneous beams is being used to speed up the sky coverage. Together with better receivers, this will improve the sensitivity by a factor of 5-10 for the same amount of telescope time per square degree as the Clifton et al (1992) and Johnston et al (1992) surveys. The corresponding longer integration time on each pointing means that acceleration searches will be necessary in order to find pulsars in fast binaries.

4. Glitches, Timing Noise and Braking Indices

4.1. Glitches

In general, radio pulsars are excellent clocks, particularly the MSPs. There are however many pulsars which show substantial departures from a regular slow down, making the rotation unpredictable. These departures are manifest in two forms, sudden instantaneous spin ups called glitches and random walk wanderings called timing noise. Both these effects are most prevalent in young pulsars, but do also occur in older pulsars. The unpredictability and randomness of these effects leads to considerable difficulties in determining braking indices. On the other hand they result from the dynamics of the interior of neutron stars and thereby provide a window through we can hope to peer into the interior.

Alpar (these proceedings) has discussed the nature and theories of glitches in detail. The basic properties of glitches include a step in rotation period of $$\Delta P/P = 10^{-9} - 10^{-5}$$, a step in rotation period derivative $$\Delta \dot{P}/\dot{P} \sim 10^{-3}$$ and an exponential recovery (Lyne, Shemar, & Smith 1997). The similarity of $$\Delta \dot{P}/\dot{P}$$ for most glitches provides indisputable evidence both for the vortex pinning model and evidence against the crust cracking model (Alpar, these proceedings). Long term regular monitoring of old favourites including the Crab and Vela has been continued and several new glitches have been observed (Lyne, Pritchard, & Smith 1993, Arzoumanian 1994), including a giant glitch in PSR B1757-24 (Lyne et al. 1996a). Some groups continue to monitor individual pulsars such as Vela for up to 18 hours per day (McCulloch 1996).

At the time of writing, 52 glitches have been observed in 21 pulsars. These 21 pulsars have a median age of 150,000 years, with 10 of them having ages less than the (arbitrary) 100,000 year boundary between young and other pulsars. Of the 52 observed glitches, 40 have occurred in young pulsars, showing that young pulsars glitch more often than older pulsars. There have already been 21 glitches detected in the pulsars found in the high frequency surveys (Section 3). This large number of glitches has now allowed statistical studies which indicate that post-glitch relaxations can be separated into two exponential components for most pulsars (Shemar, Lyne, & Smith 1996).

Glitches are associated with high $$\dot{P}$$ young pulsars and are rare. Most of the pulsars that have glitched have done so only once, indicating that the time scale for glitches is long compared to the observation time scale of a few years. Many of the pulsars near the top right of this plot have a negative $$\ddot{P}$$ which is an indication that these pulsars have glitched in the past (Lyne 1996). From an analysis of many glitches Lyne (1996) also demonstrated that glitch activity peaks for pulsars with ages of $$\sim 20,000$$ years.

4.2. Timing Noise

Timing noise is characterised by random walk phase wandering of the pulses relative to a simple slow-down model. Timing noise is generally very red and the timing residuals relative to a simple slow-
down model are often dominated by a cubic term. Hence, the second time derivative of the period $\dot{P}$ provides a simple way (there are many others) of measuring the amount of timing noise. Timing noise is greatest in young pulsars with large $\dot{P}$ (Lyne 1996, Arzoumanian et al. 1994). While most millisecond pulsars have very small period derivatives and are found to be very stable, PSR B1937+21, which has a relatively high $\dot{P}$ for a millisecond pulsar, may have shown detectable timing noise (Kaspi, Taylor, & Ryba 1994).

An enormous timing database (equivalent to over 3500 years of data on a single pulsar) has been collected at Jodrell Bank and is presently being analysed (Martin, Lyne, & Pritchard 1997). This will allow a very complete understanding of timing noise and improve on previous studies (Arzoumanian 1995). The time span of data collected for a number of MSPs will soon be long enough to assess the extent to which timing noise occurs more generally in the fastest pulsars (Taylor 1996). In this respect the next few years should establish whether or not pulsars can really be used as long term standards of time.

### 4.3. Braking Indices and Spin down evolution

The second derivative of the period can be measured for many pulsars. The vast majority however, are corrupted by timing noise and are therefore not associated with steady spin down. As a result there are only four pulsars for which the measured braking indices ($n$) are believed to be associated with the steady spin down (Lyne et al. 1996).

- B0531+21 $2.51 \pm 0.01$
- B0833–45 $1.4 \pm 0.2$
- B1509–58 $2.837 \pm 0.001$
- B0540–69 $2.24 \pm 0.04$

If braking indices are so low for most pulsars (recall $n = 3$ for magnetic dipole braking), this not only has implication for the braking mechanism, but also for the implied velocities of pulsars claimed to be associated with SNRs. The true ages of pulsars would be greater and hence the implied velocities would be smaller (Lyne et al. 1996). If the evolutionary tracks based on the above values for $n$ are compared with the present position of these pulsars and the position of the main population in Figure 1, it becomes clear that these 4 pulsars are not evolving towards the main population (Camilo 1996). There are several question that arise from this. Why is the area of the $P - \dot{P}$ diagram to which these pulsars are evolving devoid of pulsars? Where are the young pulsars that are feeding into the main population? Will $n$ increase later in the evolution so that these pulsars do enter the main population? Even though there are more theories and selection effects than there is room to discuss here, the answer to the above puzzle is not clear.

### 5. High Energy Observations

Radio timing observation of pulsars provides precision of measurement that is unlikely to be surpassed by other techniques. This precision has led to an astounding range of experiments and measurable effects that have probed fundamental physics at the deepest level. However, when it comes to studying the emission mechanisms and magnetospheres of pulsars the story is different. Such a small fraction ($< 0.1\%$) of the spin down energy is emitted at radio wavelengths that we often hear the analogy: “Trying to understand the emission mechanisms and magnetospheres of pulsars is like standing outside a factory with no windows and trying to work out what they are making inside by listening to the noises from the factory”.

In the X-ray and $\gamma$-ray bands the fraction of the spin down energy radiated approaches a few percent. This then gives a much better constraint on the emission and magnetospheric processes and is one of the prime purpose for which these high energy observations are made. The relevance to young pulsars is straight forward. All six of the pulsars detected in $\gamma$-rays are young (Kanbach, these proceedings). A large fraction of the pulsars detected in X-rays are young (Becker & Trümper 1997). Young pulsars detected at higher energies are noted in column 8 of Table 2.
Thermal components from the cooling of the neutron star surface are detected for 3 pulsars of which only Geminga is young. These observations provide direct constraints on the nature and composition of the neutron star atmospheres. However, when the thermal components are removed and the non-thermal components are considered for all the X-ray detected pulsars there is a strong linear correlation between the X-ray luminosity and the spin down energy (Becker & Trümper 1997). This correlation extents over several orders of magnitude and is remarkable given the uncertainties in the distances of at least 30% (Taylor & Cordes 1993).

5.1. Timing

Radio pulsar timing at wavelengths other than radio has until recent times been mostly restricted to two pulsars, the Crab and PSR B0540−69 at optical wavelengths, although there was also some timing of Vela (Manchester et al. 1984). Caraveo and others (this proceedings) give more detailed discussions of timing at these wavelengths. There was extensive optical timing of the Crab during the 1980’s (Lohsen 1981) which resulted in the detection of glitches (Lohsen 1977, Groth 1975) and also studies of the random walk nature of timing noise (Cordes 1980). Recently there have been simultaneous timing studies of the radio giant pulsars and gamma ray pulsations (Lundgren et al. 1997): PSR B0540−69 was discovered in X-rays (Seward, Harnden, & Helfand 1984) but most of the timing including the measurements of the braking index has been at optical wavelengths (Middleitch, Pennybacker, & Burns 1987, Manchester & Peterson 1989, Gouiffes, Finley, & Ogelman 1992). It was eventually detected in the radio after some very long integrations by radio search standards (Manchester et al. 1993). Recently braking indices for the Crab and PSRs B0540−69 and B1509−58 have been determined from X-ray timing observations using Ginga (Nagase et al. 1990). The gamma ray pulsar Geminga has not been detected at radio wavelengths but is mentioned here due to its similarity to Vela and other radio pulsars. There has been a considerable amount of timing of Geminga, in particular using COS B (Bignami & Caraveo 1992, Grenier et al. 1994) and SAS 2 (Mattox et al. 1992) which accumulated over 10 years of timing data.

6. ISM Interactions

6.1. Jets and/or Plumes

There are a number of pulsars which may be responsible for jets (plumes), though none of these jets (plumes) are known to be relativistic. The X-ray band offers the most prospects, with claims of X-ray jets for at least 6 pulsars. In some cases (PSRs B0355+54, B1055−52, B1929+10) these linear X-ray sources can be interpreted as mini-Crab nebulae, resulting from non-collimated relativistic particles confined by ram pressure as the pulsar moves through the ISM, leaving a wake of X-ray emission (Feigelson 1989, Helfand 1984, Yancopoulos, Hamilton, & Helfand 1994).

There are several cases in which this interpretation does not fit with the observations and the case for collimated emission is stronger. For the Vela pulsar (B0833−45) the X-ray jet discovered using the Einstein observatory (Harnden et al. 1985) does not line up with the pulsar proper motion (Bailes et al. 1989, Caraveo 1996). Using a ROSAT image Markwardt and Ogelman (Markwardt & Ogelman 1995) interpreted the jet as thermal, while recent ASCA observations seemed to reveal a non-thermal spectrum (Kawai 1996). The nature of the spectrum still seems to be uncertain (Markwardt, these proceedings). There are strongly polarised linear features in the radio maps of Milne (1995) that may be associated with the X-ray jet, although these have not been interpreted as a radio jet. Tamura et al. (1996) recently used ASCA observations of PSR B1509−52 to suggest that it has both a non-thermal X-ray jet generated by the pulsar and a thermal X-ray nebula that is created at the working surface of the jet with the ISM.

Apart from the Crab pulsar (see §6.2), there is little evidence for jets from radio pulsars at other wavelengths, despite some concerted searches for them.
In particular, at radio wavelengths the regions around numerous pulsars have been mapped using the VLA (Cohen et al. 1983), with no convincing evidence for jets, except for PSR B1610–50 in the supernova remnant Kes 32 (Roger et al. 1985). Maps at 843 MHz show a well collimated (although thermal, non-polarised) jet emerging from the SNR and then spreading into a wide plume. Only the main part of the remnant is detected at X-ray wavelengths (Kawai 1996). Many deep optical images have been obtained in order to study emission from the pulsars or their companions. The only pulsar (other than the Crab) with a candidate optical jet is PSR B0540–69 (Caraveo 1996). This was obtained with HST and is seen as a weak double sided linear feature lying across the pulsar in an H α light.

6.2. The Crab Pulsar and its Nebula

With no fewer than three jets the Crab pulsar must be considered to be as bizarre as the other Galactic jet sources such as SS133 and GRO J1655—40. The three jets are referred to as southeast, northwest and north.

A ROSAT image of the inner Crab nebula (Aschenbach 1992), confirmed the presence of the torus (Brinkmann, Aschenbach, & Langmeier 1985) and revealed a bright jet southeast of the pulsar. This jet appears to be aligned with the spin axis and is perpendicular to the plane of the torus (Hester et al. 1995) indicating the presence of collimated relativistic particles from the poles. With increasing distance from the pulsar, it becomes wider and bends southward. Wide field ground based images reveal a very similar but slightly more extended structure in line free optical continuum light. High resolution HST images in a similar band reveal two knots at 1,400 AU and 10,000 AU from the pulsar due to shocks in the inner jet (Hester et al. 1993). Future images of a similar quality and resolution should allow the measurement of the proper motion of the knots, giving some indication of the velocity of the jet. The VLA map of Bietenholz and Kronberg (1990) shows no evidence for a corresponding radio jet.

A similar but less well defined X-ray structure in the opposite (northwest) direction is interpreted as material compressed by the counter jet. In the optical images there are several features which run parallel to the edges of the counter jet. From a comparison of images taken at different epochs these have been shown to have proper motions perpendicularly away from the jet (Hester et al. 1995). Again in the radio maps, there is no evidence for a radio counter jet (Bietenholz & Kronberg 1990).

A third unrelated jet in a northerly direction, associated with the Crab nebula was found in a deep optical III aJ plate (van den Bergh 1970), although it was also present on isophote drawings (Wood 1957). The jet was detected in the emission lines OIII, Hα and NII, indicating that it has a non-thermal origin (Gull & Fesen 1982). It is clearly present in radio maps made with the VLA (Velusamy 1984, Frail et al. 1995). The jet is highly polarised and non-thermal with the local magnetic field lines running parallel to the jet (Wilson, Samarasingha, & Hogg 1985, Bietenholz & Kronberg 1990). Recent proper motion measurements by Fesen and Staker (1993) and Marcelin et al. (1990) are consistent with less precise earlier results and show that the jet is expanding along its length at 2500 km s⁻¹ and perpendicular to its length at 260 km s⁻¹. Using these velocities and the present jet size suggest that it formed around the same time as the pulsar. Unlike the other jets, this jet does not appear to be replenished by the pulsar.

6.3. Bow Shocks, Bullets and Plerions

There are a number of objects associated with pulsars which result from the emission of relativistic particles which are not collimated. These are briefly mentioned in this paragraph, with references to recent reviews. Pulsar wind nebulae result from bow shocks where pulsar winds are balanced by ram pressure in the interstellar medium (ISM) (Cordes 1996). While these objects are rare, they have been detected in Hα, soft X-rays and radio and may be used to determine pulsar distances, radial velocities, ISM neutral hydrogen content and the soft X-ray compo-
sition of the pulsar winds. Recently many have been observed in X-rays using ASCA \( \text{Kawai 1996} \). There are presently four eclipsing pulsars known and all of these are millisecond pulsars \( \text{Fruchter 1996} \). In such systems, a significant fraction of the pulsars' flux at all wavelengths impinges on the companion and heats it. For two of the four systems this is clearly observed as an optical brightening of the companion at superior conjunction, and offers constraints on the composition of the pulsar wind. Finally, there is the case of bullets around the Vela supernova remnant \( \text{Aschenbach, Egger, & Trümp 1995, Strom et al. 1995} \). These are detected in both X-rays and radio and appear to be lumps of material ejected at the time of the supernova explosion.

7. Birth Velocities

For many years, there has been a growing body of evidence that radio pulsars are born with large recoil velocities:

- Large scale height of pulsars \( \text{Lyne, Manchester, & Taylor 1985} \)
- Large scale height of LMXBs \( \text{van Paradijs & White 1995} \)
- Large observed proper motions \( \text{Harrison, Lyne, & Anderson 1993} \)
- Pulsars found outside SNRs \( \text{Frail, Goss, & Whiteoak 1994} \)
- Bow shocks in the ISM \( \text{Cordes 1996} \)

Lyne and Lorimer \( \text{(1994)} \) demonstrated that the main population of pulsars is devoid of many high velocity pulsars. This is because during their observable lifetime, their velocity is large enough to have allowed them to leave the Galaxy. In order to determine the mean pulsar birth velocity of \( 450 \pm 90 \text{ km s}^{-1} \) they used a sample of young pulsars. The present small sample of young pulsars is a fundamental limitation and the many young pulsars that should be found in the new surveys (Section 3) will redress this problem.

7.1. Evidence for Kicks from Asymmetric Supernovae

The mean birth velocity of \( 450 \pm 90 \text{ km s}^{-1} \) is 3 times higher than previous estimates. One of the most important questions associated with this is whether such velocities can be produced by orbital motions, or whether the neutron stars receive kicks from asymmetric supernova explosions. Van den Heuvel and van Paradijs \( \text{(1997)} \) summarised several pieces of evidence that cannot be explained without kicks:

- Misaligned spin and orbit of PSR J0045–7319 \( \text{Kaspi et al. 1996} \)
- Misaligned spin and orbit of PSR B1534+12 \( \text{Wolszczan 1992} \)
- Eccentricities of Be-Xray binaries \( \text{Verbunt & van den Heuvel 1995} \)
- Rarity of double neutron star systems \( \text{Bailes 1996} \)
- Rarity of Galactic LMXBs \( \text{van den Heuvel & van Paradijs 1997} \)

All of these are very strong evidence in favour of kicks, except possibly the misaligned spin and orbit of PSR B1534+12, since the interpretation of the polarimetry is still ambiguous \( \text{Arzoumanian et al. 1996} \). The following additional pieces of evidence also support the kick hypothesis:

- No pulsars found in OB and Be star surveys \( \text{Philipp et al. 1996} \)
- Kicks required to produce pulsar spin rates \( \text{Phinney 1997} \)
- Misaligned spin and orbit of PSR B1259–63 \( \text{Melatos et al. 1995} \)
- Rarity of Galactic MSPs \( \text{Tauris & Bailes 1996} \)

Recently Phinney \( \text{(1997)} \) reiterated the difficulty of forming a rapidly rotating neutron star directly from the core collapse during a supernova explosion. He demonstrated that a misdirected birth kick could provide both the extra angular momentum required for the rapid spin as well as the observed recoil velocities. This mechanism suggested that for a given
strength of birth kicks, there would be an anticorrelation between spin rate and recoil velocity. Another implication is that a significant fraction of young pulsars would be born with periods ranging 1 to 1000 ms. We should therefore see some pulsars in supernova remnants with long periods. While there may be selection effects against finding such pulsars notable examples are PSRs B2334+61 \( (P = 495\text{ ms}) \) and B1758–23 \( (P = 416\text{ ms}) \) (Kulkarni & Frail 1993).

If Phinney (1997) is correct then the population of truly young pulsars may include many pulsars with considerably lower spin down energies than those which are the main subject of this review.

8. Associations with Supernova Remnants

The association of neutron stars with supernova remnants (SNRs) began with Baade and Zwicky (1934). The discovery of the Crab pulsar in the Crab nebula provided the first evidence supporting their bold proposition (Staelin & Reifenstein 1968). The typical observable lifetime of SNRs is comparable to the ages of the young pulsars we are discussing here, so that many young pulsars are likely to be found in or near the remnants from the supernovae which formed them. The task of identifying which pulsars are associated with which SNRs is difficult. There are now some 215 SNRs known (Green 1996) and the probability of chance positional coincidences is significant.

Kaspi (1996) listed several additional questions that require a positive answer for a pulsar and SNR to be physically associated:

- Do independent distance estimates agree?
- Do independent age estimates agree?
- Is the implied velocity reasonable?
- Is there any evidence for interaction?
- Are the pulsar proper motion and position offset consistent?
- Are the overall statistics sensible?

In many cases, the pulsar is well outside the remnant that it is claimed to be associated with. As a result there are several cases in which the implied velocity is over 1000 km s\(^{-1}\). Given the uncertainty in the distances and ages, particularly for SNRs, the most pertinent of the above questions is the consistency of the pulsar proper motion and its present position with respect to the remnant. Unfortunately proper motion measurements are available for only a few of the 28 pulsars which are claimed to be associated with supernova remnants.

Kaspi (1996) drew up a score sheet for the 28 claimed associations based on the above questions. A summary of the results for young pulsars is given in the last column of Table 2, with 6 definite associations and 5 probable. Including PSR B1951+31 \( (\text{age} = 107,000\text{ years}) \) gives a total of 7 definite associations. The remaining 16 candidate associations are either not real or lack sufficient observational evidence to determine their credibility. Similar questions are addressed by Frail (these proceedings) who provides a census of all types of neutron stars associated with SNRs.

I thank Ed van den Heuvel, Duncan Lorimer and Dale Frail for discussions on pulsar velocities, Jean-Francois Lestrade for unpublished parameters, Andrew Lyne and Graham Smith for helpful discussions and the organisers for a fun and productive meeting.

REFERENCES

Arzoumanian, Z. 1995. PhD thesis, Princeton University
Arzoumanian, Z., Nice, D. J., Taylor, J. H., & Thorsett, S. E. 1994, ApJ, 422, 671
Arzoumanian, Z., Phillips, J. A., Taylor, J. H., & Wolszczan, A. 1996, ApJ. Submitted
Aschenbach, B. 1992, Zeiss Information with Jena Review, 1, 6
Aschenbach, B., Egger, R., & Trümper, J. 1995, Nature, 373, 587
Baade, W. & Zwicky, F. 1934, Proc. Nat. Acad. Sci., 20, 254
Bailes, M. 1996, in Compact Stars in Binaries, IAU Symp. 165, ed. J. van Paradijs, E.P.J. van den Heuvel, & E. Kuulkers, (Dordrecht: Kluwer), 213
Bailes, M., Manchester, R. N., Kesteven, M. J., Norris, R. P., & Reynolds, J. E. 1989, ApJ, 343, L53
Becker, W. & Trümper, J. 1997, A&A. Submitted
Nagase, F., Deeter, J., Lewis, W., Dotani, T., Makino, F., & Mitsuda, K. 1990, ApJ, 351, L13
Philp, C. J., Evans, C. R., Leonard, P. J. T., & Frail, D. A. 1996, Astron. J., 111, 1220
Phinney, E. S. 1997, in Pulsar Timing, General Relativity, and the Internal Structure of Neutron Stars, ed. Z. Arzoumanian, E. P. J. van den Heuvel, & J. van Paradijs, Elsevier, In Press
Roger, R. S., Milne, D. K., Kesteven, M. J., Haynes, R. F., & Wellington, K. J. 1985, Nature, 316, 44
Seward, F. D., Harnden, F. R., & Helfand, D. J. 1984, ApJ, 287, L19
Shemar, S. L., Lyne, A. G., & Smith, F. G. 1996, MNRAS. In prep.
Staelin, D. H. & Reifenstein, III, E. C. 1968, Science, 162, 1481
Strom, R., Johnston, H. M., Verbunt, F., & Aschenbach, B. 1995, Nature, 373, 590
Tamura, K., Kawai, N., Yoshida, A., & Brinkmann, W. 1996, PASJ, 48, L33
Tauris, T. M. & Bailes, M. 1996, A&A. In press
Taylor, J. H. 1996, in Pulsars: Problems and Progress, IAU Colloquium 160, ed. S. Johnston, M. A. Walker, & M. Bailes, Astronomical Society of the Pacific, 65
Taylor, J. H. & Cordes, J. M. 1993, ApJ, 411, 674
van den Bergh, S. 1970, ApJ, 160, L27
van den Heuvel, E. P. J. & van Paradijs, J. 1997, ApJ. Submitted
van Paradijs, J. & White, N. 1995, ApJ, 447, L33
Velusamy, T. 1984, Nature, 308, 251
Verbunt, F. & van den Heuvel, E. P. J. 1995, in X-ray binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel, Cambridge University Press, 457
Wilson, A. S., Samarasinha, N. H., & Hogg, D. E. 1985, ApJ, 294, L121
Wolszczan, A. 1992, in X-ray Binaries and Recycled Pulsars, ed. E. P. J. van den Heuvel & S. A. Rappaport, (Dordrecht: Kluwer), 93
Wood, M. A. 1957, Bull. Astron. Inst. Net., 14, 39
Yancopoulos, S., Hamilton, T. T., & Helfand, D. J. 1994, ApJ, 429, 832

This preprint was prepared with the AAS LaTeX macros v4.0.

### Table 1: Median values of parameters for three observed populations of pulsars

| Parameter | Young | Normal | MSP |
|-----------|-------|--------|-----|
| $P$ (ms)  | 150   | 622    | 4.6 |
| $\dot{P}$ | $1.2 \times 10^{-13}$ | $1.8 \times 10^{-15}$ | $2.0 \times 10^{-20}$ |
| Age (years) | $2.0 \times 10^4$ | $5.5 \times 10^6$ | $5.0 \times 10^9$ |
| $B$ (Gauss) | $4.9 \times 10^{12}$ | $1.0 \times 10^{12}$ | $3.6 \times 10^8$ |
| $\dot{E}$ (ergs s$^{-1}$) | $1.3 \times 10^{36}$ | $2.4 \times 10^{32}$ | $5.0 \times 10^{33}$ |
| DM (cm$^{-3}$ pc) | 219 | 89 | 22 |
| Dist. (kpc) | 4.3 | 3.8 | 1.3 |
| $z$ (kpc) | 0.04 | 0.35 | 0.38 |
| S400 (mJy) | 10 | 11 | 15 |
| $L$ (mJy kpc$^2$) | 260 | 130 | 35 |
| Number | 23 | 651 | 59 |
Table 2: Young Energetic Radio Pulsars. O – optical, X – X-rays, $\gamma$ – $\gamma$-rays, I – infra-red, J – jet, N – nebula, G – glitches, B – bow shock, Y – yes, P – probably, ? – maybe, U – unlikely

| Name            | P (sec) | Pdot ($10^{-15}$) | Age (kyr) | log($E$) | log($B$) | $b$ | Comment | SNR |
|-----------------|---------|-------------------|-----------|----------|----------|-----|---------|-----|
| B0531+21        | 0.033   | 420.9             | 1.2       | 38.6     | 12.6     | -5.8| O,X,\gamma,I,J,N,G | Y  |
| B1509–58        | 0.150   | 1536.5            | 1.5       | 37.2     | 13.2     | -1.2| X,\gamma,J,N       | P  |
| B0540–69        | 0.050   | 479.0             | 1.6       | 38.2     | 12.7     | -31.5| O,X                 | Y  |
| B1610–50        | 0.231   | 496.0             | 7.3       | 36.2     | 13.0     | +0.2| X,J,N               | ?  |
| B0833–45        | 0.089   | 124.1             | 11        | 36.8     | 12.5     | -2.8| O,X,\gamma,J,N,G   | Y  |
| B1338–62        | 0.193   | 253.2             | 12        | 36.1     | 12.9     | -0.0| G                   | Y  |
| B1757–24        | 0.124   | 128.0             | 15        | 36.4     | 12.6     | -0.9| G                   | Y  |
| B1800–21        | 0.133   | 134.3             | 15        | 36.3     | 12.6     | +0.2| X,G                 | P  |
| B1706–44        | 0.102   | 93.0              | 17        | 36.5     | 12.5     | -2.7| X,\gamma,G         | ?  |
| B1046–58        | 0.123   | 96.0              | 20        | 36.3     | 12.5     | +0.6| X,N                 | U  |
| B1757–30        | 0.606   | 465.3             | 20        | 34.9     | 13.2     | +0.2| G                   | U  |
| B1853+01        | 0.267   | 208.4             | 20        | 35.6     | 12.9     | -0.5| B                   | Y  |
| B1823–13        | 0.101   | 74.9              | 21        | 36.5     | 12.5     | -0.7| X,G                 | ?  |
| B1727–33        | 0.139   | 85.0              | 25        | 36.1     | 12.5     | +0.1| G                   | ?  |
| B1643–43        | 0.231   | 112.7             | 32        | 35.6     | 12.7     | +1.0| P                   |    |
| B1930+22        | 0.144   | 57.5              | 39        | 35.9     | 12.5     | +1.6| U                   |    |
| B2334+61        | 0.495   | 191.8             | 40        | 34.8     | 13.0     | +0.2| X                   | P  |
| J0633+1746      | 0.287   | 104.6             | 43        | 35.2     | 12.7     | +0.5| O,X,\gamma,No Radio| U  |
| B1758–23        | 0.415   | 112.9             | 58        | 34.8     | 12.8     | -0.1| G                   | P  |
| J1105–6107      | 0.063   | 15.8              | 63        | 36.4     | 12.0     | -0.9| ?                   |    |
| B1727–47        | 0.829   | 163.6             | 80        | 34.1     | 13.1     | -7.7| U                   |    |
| B0611+22        | 0.334   | 59.6              | 88        | 34.8     | 12.7     | +2.4| ?                   |    |
| B1916+14        | 1.180   | 211.4             | 88        | 33.7     | 13.2     | +0.9| U                   |    |

Table 3: Example high frequency surveys. Note, the Parkes survey [Johnston et al. 1992] used two recording systems in parallel, hence the duplicate parameters. Parameters for the Nancay were kindly provided by J-F. Lestrade

| Parameters | Jodrell | Parkes | Nancay | PKS MB | JOD MB |
|------------|---------|--------|--------|--------|-------|
| Nbeams     | 1       | 1      | 1      | 13     | 4     |
| $b$        | $\pm 1$ | $\pm 4$| $\pm 3$| $\pm 5$| $\pm 5$|
| $l_{min}$  | -5      | -90    | -15    | -90    | 20    |
| $l_{max}$  | 100     | 20     | 180    | 20     | 100   |
| $T_{int}$ (min) | 10     | 2.5    | 2      | 30     | 30    |
| $T_{samp}$ (ms) | 2.0   | 1.2/0.3| 0.06   | 0.25   | 0.25  |
| Bandwidth (MHz) | 40    | 320/80 | 150    | 288    | 64    |
| Channels (MHz)  | 5     | 5.0/1.0| 1.6    | 3.0    | 3.0   |
| $S_{sys}$ (Jy)  | 70    | 70     | 45     | 40     | 40    |
| $S_{min}$ (mJy) | 2.0   | 1.0    | 0.4    | 0.1    | 0.2   |
| Pulsars found  | 40    | 46     | ....   | ....   | ....  |
| Accn. search   | No    | No     | No     | Yes    | Yes   |