The implications of radio-quiet neutron stars

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ABSTRACT

We collate the evidence for rotation-powered neutron stars that are visible as X-ray sources and not as radio pulsars. To date, ten objects have been proposed and one, Geminga, has been confirmed as a pulsar by the detection of 4.2 Hz pulsations. Several indicators have been used to support the proposition that the X-ray sources are isolated neutron stars, including high X-ray to optical/radio flux ratios, a constant X-ray flux and coincidence with a $\gamma$-ray source. Seven of the published neutron star candidates are located near the centres of supernova remnants, two of them within plerions, suggesting that these are young objects ($\tau < 20,000$ yr). The remaining candidate neutron stars have no associated supernova remnant and may be older systems, powered either by their rotation, like Geminga, or possibly by accretion from the interstellar medium.

Quantitative upper limits exist for the radio fluxes of eight of the ten objects and reveal a population at least an order of magnitude less luminous at radio wavelengths than known radio pulsars of similar power or age. These could be intrinsically low luminosity pulsars, but this implies an overpopulation of neutron stars relative to the galactic supernova rate. A simple alternative explanation within the context of existing pulsar models is that these objects are pulsars in which the radio beams are directed away from Earth. They are still visible as X-ray sources because the weakly modulated, surface (thermal) emission, which dominates the soft X-ray emission in most young to middle-aged radio pulsars, is radiated in all directions. In the cases where hard X-ray or $\gamma$-ray fluxes are seen, the beaming explanation implies different emission sites for the non-thermal high-energy radiation and the unseen radio beams. From the number of candidate neutron stars and radio pulsars younger than 20,000 years and within 3.5 kpc, the radio beaming fraction of young pulsars is estimated to be roughly 50% and certainly much less than 100%. We find the local neutron star birth rate to be at least 13 Myr$^{-1}$kpc$^{-2}$. This extrapolates to a galactic rate of one neutron star born every $\sim 90$ years. We conclude that probably all neutron stars are born as radio pulsars and that most young, nearby pulsars have already been discovered.

Key words: stars: neutron, stars: X-rays

1 INTRODUCTION

The Princeton pulsar catalogue (Taylor et al. 1993) now contains entries for over 700 radio pulsars, collected from many pulsar surveys and targeted searches. In addition to the radio pulsars, there is a single entry with no measured 400 MHz or 1400 MHz flux: the X- and $\gamma$-ray pulsar known as Geminga (Halpern & Holt 1992, Bertsch et al. 1992). The tight upper limits on its radio flux give Geminga a luminosity limit several orders of magnitude below those seen in known radio pulsars of similar age or power and place this source apart from the general population.

At high energies, there is no obvious difference between Geminga and the $\sim 20$ other pulsars in the Princeton catalogue that have been detected as X-ray sources. Seven, including Geminga, have also been seen by $\gamma$-ray telescopes. The high energy detections are limited to the very brightest objects and sample a more powerful and nearby set of pulsars than the deeper radio searches. In X-rays, the luminosity is approximately correlated with pulsar spin-down power, $\dot{E}$, so that $\dot{E}$ divided by the square of the distance $d$ is a convenient measure of the detectability of a radio pulsar as an X-ray source. The radio pulsars detected in the ROSAT (0.1–2.4 keV) band all have $\dot{E}/d^2 \gtrsim 10^{34}$ erg s$^{-1}$kpc$^{-2}$ and, conversely, nearly all of the radio pulsars fitting this criterion have been detected. It is important to note that the detections include not only young, powerful pulsars, but also old and millisecond pulsars that are less powerful but are
nearby. Taking distance uncertainties into account, the high level of X-ray detections therefore implies that most radio pulsars are X-ray pulsars. The inverse, that most or all X-ray pulsars are radio pulsars, need not be true: Geminga is a specific counter-example. Note that the term ‘X-ray pulsar’ is taken here and throughout this paper to mean a rotation-powered pulsar observed in X-rays, not a neutron star powered by accretion from a stellar companion or from a residual accretion disk.

Geminga is a 350,000-year-old pulsar at a distance of only $\sim 160$ pc. Its proximity has allowed very low luminosity limits to be calculated from the limits on its radio flux and it has been labelled ‘radio-quiet’. However, a low flux density does not necessarily mean that the radio luminosity is low. It could simply mean that the radio beam is not visible from the Earth. In this paper we will define a radio-quiet pulsar as a rotation-powered pulsar which has not been detected at 400 or 1400 MHz and which therefore has a low inferred luminosity at these frequencies. This definition does not distinguish between explanations based on luminosity and beaming, nor does it equate radio-quiet with radio-silent.

Radio-quiet pulsars are extremely difficult to identify because photon statistics at high energies make useful pulsation searches impossible for all but the brightest sources. The first evidence for a radio-quiet pulsar is usually an extreme spectrum: bright in X-rays and/or $\gamma$-rays but very silent. No allowance for the bias is made towards high X-ray luminosities and an $\dot{E}$ derived from it may be underestimated. No allowance for the trend includes only the detected X-ray pulsars, it is biased towards high X-ray luminosities and an $\dot{E}$ derived from it may be underestimated. No allowance for the bias is made in this paper because the candidate pulsars are also selected as X-ray sources.

For 3C58 and CTA 1, the pulsars provide an independent way to estimate the power of the embedded pulsars. Seward & Wang (1988) found an empirical relationship between the X-ray luminosity of a plerion and the spin-down power of the pulsar powering the plerion. For CTA 1, Slane et al. (1997) used this relationship to estimate a spin-down power of $1.7 \times 10^{36}$ erg s$^{-1}$. For 3C58, similar considerations of the X-ray synchrotron emission yield $\dot{E} = (2-4) \times 10^{36}$ erg s$^{-1}$ (Helfand et al. 1995), while $\dot{E} = 1.5 \times 10^{36}$ erg s$^{-1}$ is required to explain a radio filament near to the candidate pulsar in terms of a shock in the pulsar wind (Frail & Moffett 1993).

The pulsar candidates in CTA 1 and G078.2+2.1 are coincident with $\gamma$-ray sources, providing a third way to estimate the spin-down power. While the relationship between $\gamma$-ray luminosity and spin-down power is still unclear (Fierro 1995), Brazier et al. (1996, 1997) showed that the $\gamma$-ray luminosities inferred for the two candidates were consistent with those of Vela and PSR B1706–44. In both cases, the spin-down power derived from the X-ray flux is more than an order of magnitude lower than the $\gamma$-ray comparison would suggest. The estimates from the $\gamma$-ray fluxes are listed in Table 1. An intermediate spin down power is used in this paper for these two objects.

It would be unwise to treat the candidates in supernova remnants as a statistical sample. ROSAT, used to observe each of them, has not observed many of the Galaxy’s SNRs, and identification of a neutron star candidate depends on the interests of the observer as well as an object’s physical properties. In addition, the sensitivity to point sources within an SNR varies with the intensity profile of the SNR emission, so that objects close to the rim of a SNR may be submerged in bright diffuse emission. In RCW 103, for example, the ASCA observation has confirmed the status of the point source 1E 161358–5055 by separating it spectrally from the SNR (Gotthelf et al. 1997).

In addition to the candidate pulsars within supernova remnants, there are a further two candidates, plus the confirmed pulsar Geminga, which are not associated with SNRs. The list is short because there is much less to attract the attention of observers than in the case of an SNR. Without the bonus of a supernova remnant, it is also difficult to estimate the distances to these pulsar candidates or to guess their ages. Nevertheless, the one confirmed radio-quiet pulsar is in this group.

### 2.1 Candidate pulsars within SNRs

#### 2.1.1 RXJ0002+6246 (G117.7+0.6)

A faint X-ray arc was discovered by Hailey & Craig (1995) in the periphery of ROSAT PSPC images of the SNR CTB 1. The arc was proposed to form part of a previously unknown shell-type supernova remnant, G117.7+0.6 [footnote: The proposed remnant is centred at galactic coordinates $(l,b) = (117.4, 0.3)$. The position $(117.7, 0.6)$ appears to be a mis-conversion from celestial to galactic coordinates.] at a distance of $\sim 3$ kpc. An unidentified point source, RXJ0002+6246, is clearly visible 10 arcmin from the central position. None of the nearby optical sources was found to be a plausible counterpart and there is no radio source.
listed at this position, suggesting that RXJ0002+6246 could be a radio-quiet neutron star associated with the proposed remnant, possibly with a pulsation period of 242 ms (Hailey & Craig 1995). Because no quantitative limit to the radio flux is given, RXJ0002+6246 will not be included in this paper as a radio-quiet pulsar candidate.

### 2.1.2 RXJ0007.0+7302 (CTA 1)

This object lies in the north of the CTA 1 supernova remnant, a mostly circular radio SNR with a 'blow-out' on its north-east side (Pineault et al. 1993). In X-rays, the SNR is dominated by non-thermal plerionic emission, interpreted as synchrotron emission from the relativistic particles generated by a fast pulsar (Slane et al. 1997). Slane et al. propose that the point source RXJ0007.0+7302, which is positioned at the centre of the plerion, is the pulsar, and this is supported by limits on its optical and radio flux (Brazier et al. 1997). The flux and spectrum of a persistent, unidentified γ-ray source coincident with RXJ0007.0+7302 are consistent with emission from a pulsar at the age and distance of CTA 1, leading Brazier et al. (1997) to propose that this object, like Geminga, is a γ-ray loud, radio-quiet pulsar. If we accept this proposal, the spectrum peaks in the GeV region, making this a 'Vela-like' rather than 'Crab-like' pulsar, with the faint flux in soft X-rays typical of pulsars older than a few thousand years.

### 2.1.3 RXJ0201.8+6435 (3C58)

3C58 (G130.7+3.1) is a young SNR, similar to the Crab SNR in radio spectrum and morphology, and is thought to have resulted from the supernova of AD 1181 (Clark & Stephenson 1977). Confirmation of a compact X-ray source within the plerion (Becker et al. 1982) was provided by Helfand et al. (1995). It is still unclear whether a north-south ellipticity of the X-ray source means that the object is in fact associated with a radio filament discovered by Frail & Moffett (1993) or that the apparent extent is due to the attitude reconstruction problems known to affect some ROSAT data. Helfand et al. (1995) determine that the X-ray luminosity of the plerionic SNR emission is \(4–7 \times 10^{35} \text{erg/s}\), which would require the neutron star to have a spin-down power of \(\dot{E} \approx 10^{36} \text{erg s}^{-1}\), bracketing the estimated power of \(1.5 \times 10^{36} \text{erg s}^{-1}\) needed to produce a shock at the position of the radio filament (Frail & Moffett 1993). This is much smaller than the power of known radio pulsars with such small ages. The ROSAT spectrum and the upper limit of 50% on pulsations are best modelled as thermal emission from the hot polar caps of a neutron star, not non-thermal magnetospheric pulses. The properties of the nebula and the compact source can be reconciled within the age constraints if the pulsar is relatively slow and with a surface magnetic field above \(10^{13} \text{G}\) (Helfand et al. 1995).

### 2.1.4 1E 0820–4247 (Puppis A)

A compact source close to the centre of Puppis A was first discovered in Einstein HRI images (Petre et al. 1982), but its point-like nature has only recently been confirmed (Petre et al. 1996). Stringent optical and radio limits (Petre et al. 1996, Kaspi et al. 1996) rule out most types of X-ray sources apart from a neutron star or a BL Lac with weak radio emission. The X-ray source shows no evidence of variability between observations and is less than 20% pulsed, implying that, if this is a neutron star, the soft X-ray emission is predominantly thermal rather than magnetospheric, i.e. more similar to the Vela pulsar than to the Crab. There is no visible plerion.

### 2.1.5 1E 1207.4–5209 (G296.5+10.0)

G296.5+10.0 has a symmetric ‘barrel’ morphology defined by two clear, elongated radio arcs; its age is estimated to be roughly 20,000 years (Seward & Wang 1988). Using Einstein observations of the remnant, Kellett et al. (1987) showed

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### Table 1. Candidate isolated neutron stars and their properties.

| Name                  | \(F_{\gamma}(0.1–2.4 \text{keV})\) \((\text{erg cm}^{-2} \text{s}^{-1})\) | \(\dot{E}\) \((\text{10}^{30} \text{erg s}^{-1})\) | \(S_{400}\) \((\text{mJy})\) | \(S_{1400}\) \((\text{mJy})\) | SNR name | Common name | dist \((\text{kpc})\) | age \((\text{10}^{3} \text{yr})\) | refs |
|-----------------------|-------------------------------------------------|---------------------------------|-----------------|-----------------|------------|-------------|----------------|----------------|------|
| RXJ0002+6246          | \(2 \times 10^{-13}\)                          | ?                               | < 0.1           | < 0.1           | G114.7+0.6 | CTA1        | 3              | 20             | 9    |
| RXJ0007.0+7302        | \(9 \times 10^{-14}\)                          | \(7 \times 10^{6}\)            | < 1.5           | < 0.3           | G119.5+10.2 | CTA1        | 1.4            | 5–10           | 1,2,16 |
| RXJ0201.8+6435        | ?\(\text{or} \ (2–5) \times 10^{6}\)          | < 2.1                           | < 0.15          | 3C58            | 3.2        | 0.8         | 3,7,16         |                 |      |
| 1E 0820–4247          | \(3 \times 10^{-12}\)                          | \(1.7\)                         | < 0.3           | G260.4-3.4      | Pup A      | 2           | 3.7            | 4.14           |      |
| 1E 1207.4–5209        | \(2 \times 10^{-12}\)                          | \(1.0\)                         | G296.5+10.0     | PKS 1209-51/52  | 1.5        | 7           | 14.15          |                 |      |
| 1E 1634–5055          | \(7 \times 10^{-13}\)                          | < 1.5                           | < 0.1           | G332.4-0.4      | RCW103     | 3.3         | 1–3            | 11,12,14       |      |
| RXJ2020.2+4026        | \(4 \times 10^{-14}\)                          | \(7 \times 10^{6}\)            | < 5             | < 0.35          | G078.2+2.1 | γ–Cyg       | 1.5            | 10             | 10,16 |

References: 1. Slane et al. 1997; 2. Brazier et al. 1997; 3. Helfand et al. 1995; 4. Petre et al. 1996; 5. Walter et al. 1996; 6. Neuh¨auser et al. 1997; 7. Frai l & Moffett 1993; 8. Seiradakis 1992; 9. Hailey & Craig 1995; 10. Brazier et al. 1996; 11. Tuohy & Garmire 1980; 12. Gotthelf et al. 1997; 13. Stocke et al. 1995; 14. Kaspi et al. 1996; 15. Mereghetti et al. 1996; 16. Lorimer et al. 1997b.
that a compact X-ray source, 1E 1207.4–5209, close to the geometric centre of the remnant might be an isolated neutron star. Matsui et al. (1988) strengthened this claim with upper limits on the optical luminosity, while Mereghetti et al. (1996) have published further details of the effort to identify this X-ray source. They find no plausible optical counterpart down to \( m_V \sim 25 \) and place a 0.1 mJy limit at 4.8 GHz. Kaspi et al. (1996) placed a tighter 1 mJy pulsation limit at 400 MHz. Recent analysis of the ASCA/ROSAT spectrum of 1E 1207.4–5209 shows that it is thermal and can be interpreted in terms of a cooling neutron star (Vasisht et al. 1997). Less than 24% of the ASCA flux is pulsed.

2.1.6 1E 1613+48–5055 (RCW 103)

Einstein HRI observations first revealed 1E 161348–5055 as an unresolved X-ray source within RCW 103 (Tuohy & Garmire 1980). With the object lying very close to the centre of the SNR in a minimum of the diffuse shell emission, an association between the two seemed likely, but searches for optical or radio counterparts have not been successful. Kaspi et al. (1996) provide 400 MHz and 1.5 GHz pulsed flux density limits of 1.5 mJy and 0.1 mJy respectively. Recently, the point source has been observed with ASCA and separated spectrally from the bright but softer SNR shell emission (Gotthelf et al. 1997). The point source flux is probably constant on long time scales, within the errors presented by matching an ill-defined spectrum across several instruments. The age of the remnant is estimated to be 1,000–3,000 years, and the supernova responsible for RCW 103 might have been a guest star reported in 134 B.C. (Wang et al. 1986).

2.1.7 RXJ2020.2+4026 (G078.2+2.1)

The \( \gamma \)-ray source 2EG J2020+4026 (2CG078) has been linked with the G078.2+2.1 SNR by several authors, most recently Sturmer & Dermer (1995) and Esposito et al. (1996). During a detailed study of the \( \gamma \)-ray source, Brazier et al. (1996) noted the existence of a single unresolved X-ray source, RXJ2020.2+4026, at the centre of the remnant. The X-ray flux is steady and no likely optical or radio counterparts were found in subsequent searches, leaving the possibility that the X-ray and \( \gamma \)-ray fluxes were from a pulsar in the G078.2+2.1 SNR. Like RXJ0007.0+7302, the proposed pulsar is Vela-like, with a small X-ray flux relative to the \( \gamma \)-ray flux.

2.2 Isolated candidates

2.2.1 Geminga

The discovery of 4.2 Hz pulsations in the enigmatic Geminga, first in X-rays (Halpern & Holt 1992) and then in \( \gamma \)-rays (Bertsch et al. 1992), confirmed this as a pulsar, albeit one with a radio luminosity very much lower than any known radio pulsar. Recent reports that Geminga has finally been seen as a radio pulsar at very low frequencies (Kuzmin & Losovsky 1997, Malofeev & Malov 1997) do not affect the limits on its luminosity at higher frequencies, which we use here for comparison with the population of radio pulsars.

The lack of absorption of Geminga’s X-ray flux and its high \( \gamma \)-ray flux mean that Geminga must be nearby, within the approximate range 100 < \( d < 400 \) pc (Bertsch et al. 1992, Halpern & Ruderman 1993). A recent, marginal detection of parallax in Hubble Space Telescope observations gives a distance of 120–220 pc (Caraveo et al. 1996), in good agreement with the earlier estimates. The best parallax value of 160 pc will be adopted in this paper.

Knowledge of Geminga’s spin parameters and distance enables a direct comparison with radio pulsars. In particular, the spin-down power and age can be derived from the rotation period \( P \) and its first derivative \( \dot{P} \) in exactly the same way as for other pulsars.

2.2.2 MS 0317–6647

Among the list of candidate neutron stars, MS 0317–6647 is the only one to show signs of long-term variability. It is an unusual source, with no optical counterpart and a hard, featureless X-ray spectrum that is not well described by simple models (Petre et al. 1994). While it may well be a luminous X-ray binary in the spiral galaxy NGC 1313, Stokoe et al. (1995) discuss the possibility that it is an old neutron star in our own galaxy. The variability argues against a rotation-powered or cooling neutron star, leaving the option that this is an object accreting from the interstellar medium (ISM). No specific radio flux limits are available, and this object is not included further in this paper.

2.2.3 RXJ1856.5–3754

Walter et al. (1996) announced the discovery that this X-ray source was an old neutron star at a distance of about 100 pc. The source, first detected in the Einstein slew survey, is very bright, yet no counterpart was found, and the source flux did not vary. The proposed distance to the object was determined from the X-ray spectrum of the object: since the source is in the direction of a molecular cloud at \( \sim 120 \) pc, the low \( N_H \) measured from the X-ray spectrum implied that the source lay in front of the cloud. Walter et al. concluded that the object was a nearby, old neutron star, perhaps powering its X-ray emission through accretion from the interstellar medium.

Reassessments of RXJ1856.5–3754 have been published by Neuhausser et al. (1997) and Campana et al. (1997). Both groups find that their more conservative error circles for the X-ray position still include all bright optical sources, and they agree with the previous conclusion that the object is probably a neutron star. However, it has not been possible to distinguish between a “middle-aged” pulsar like Geminga and an old neutron star accreting from the ISM. Using the revised source position given by Neuhausser et al., Walter et al. (1997) have now identified a faint optical counterpart at magnitude 25.6, consistent with a neutron star. The distance to the object may be larger than claimed by Walter et al. (1996). The X-ray spectrum is well modelled by black body radiation from the surface of a neutron star at 100–170 pc. However, the X-ray spectra of radio pulsars do not give reliable distances under the same assumptions. Observations of the parallax and/or proper motion of RXJ1856.5–3754 will help to resolve its nature and distance. For the rest of this paper we will assume that it is at a distance of 120 pc.

From the ten objects listed in Table 1 we conservatively accept the eight with quantitative radio limits as good neutron star candidates, six in SNRs and two isolated. The
strong case for physical association between the first group of X-ray sources and the supernova remnants is seen more clearly if we consider the distances from the point sources to the SNR centres and the transverse velocities that these distances imply. With the exclusion of 3C58, which has no known SNR shell, these are listed in Table 2. The velocities are entirely consistent with the median of 460 km s$^{-1}$ given by this method for radio pulsars in SNRs (Frail et al. 1994) and the median of 300 km s$^{-1}$ seen in the general population of radio pulsars (Lorimer et al. 1997a). Also listed in Table 2 is the angular distance $\beta$ between the pulsar and the SNR centre, expressed as a fraction of the SNR radius. The values of $\beta$ here are smaller than in most suggested associations between radio pulsars and supernova remnants (Kaspi 1996 & references therein). It is improbable that so many unusual X-ray objects would be found near the centres of young SNRs unless there is an association. In addition, the plerions in CTA 1 and 3C58 point very strongly to active sources of relativistic particles in these SNRs. The lack of a plerion in the other SNRs, however, does not imply the reverse (Bhattacharya 1990).

For the six candidates in supernova remnants, there is therefore strong evidence that they are neutron stars. Of the two isolated candidates, Geminga is confirmed as a pulsar and RX J1856.5–3754 has properties entirely consistent with the proposition that it too is a neutron star. For the remainder of this paper, it will be assumed that all eight candidates are neutron stars.

### Table 2. Offsets of pulsar candidates from SNR centres, expressed as fractions $\beta$ of the SNR radius. The implied velocities, using the distance and age estimates in Table 1, are also given. Supernova sizes and centres are from Green’s SNR catalogue (1996) and from Petre et al. (1996). The size of the 3C58 remnant is for the plerion alone.

| Compact source | SNR | SNR radius (arcmin) | Offset (arcmin) | $\beta$ | $v$ (km s$^{-1}$) |
|----------------|-----|---------------------|----------------|--------|-----------------|
| RXJ007.0+7302  | CTA 1| 45                  | 15             | 0.33   | 730             |
| RXJ020.8+4635  | 3C58 | 3                   | ?              | ?      | ?               |
| 4E 0820–4247   | Pup A| 25                  | 6              | 0.25   | 930             |
| 4E 1207.4–5290 | G296.5+10.0| 33                | 3              | 0.10   | 200             |
| 4E 1613+5055   | RCW103| 10                 | 0.5            | 0.65   | 220             |
| RXJ020.2+4026  | G078.2+2.1| 60               | 1.5            | 0.03   | 60              |

3 COMPARING RADIO PULSARS WITH X–RAY-SELECTED NEUTRON STAR CANDIDATES

None of the eight accepted objects has been detected as a radio source. Could any of them be a normal radio pulsar? In Fig. 1 the radio luminosities, assuming 1 steradian beaming, of radio pulsars listed in the Princeton pulsar catalogue (Taylor et al. 1993) are plotted against spin-down power. Larger symbols indicate pulsars at distances of less than 3.5 kpc, directly comparable with the X-ray pulsar candidates. The axes demonstrate the rise towards a higher median luminosity, $\sim 300$ mJy kpc$^2$ at 400 MHz, $\sim 100$ mJy kpc$^2$ at 1400 MHz, for energetic pulsars (e.g. Lyne et al. 1985, Taylor & Stinebring 1986, Tauris & Manchester 1997) and the sensitivity limits of radio searches. Using Table 1, the upper limits for the seven pulsar candidates and Geminga have also been added. Each of the candidate pulsars is shown with an order of magnitude uncertainty in the spin-down power: this is intended to be illustrative and does not indicate a formal uncertainty. Note that for the candidates, both axes scale with the square of distance.

An alternative way to view these data is in terms of pulsar/candidate age, as shown in Figure 2. In this figure, the ages for the candidate neutron stars are taken to be those of the host SNR, again giving a dependence on distance. Increasing the distances in both figures, for example, would tend to make the radio limits weaker and the candidate pulsars older but also more powerful. Even taking reasonable degrees of uncertainty into account, very large increases in distance would be required to bring the radio luminosities of the candidate pulsars into the realm of known radio pulsars. There are four possible explanations for their non-detection as radio sources:

1. They have intrinsically small radio luminosities or very steep radio spectra
2. The radio beams are directed away from Earth
3. They have unusual spin parameters untested by current pulsar searches
4. They are not pulsars.

Although we have accepted all eight candidates as neutron stars, it will of course remain possible that one or more of the candidates is not a rotation-powered pulsar until each of them has been identified conclusively. Weak accretion has been suggested as a possible power source in RXJ1856.5–3754 and 1E 1207.4–5209. The accretion models fall into two types: old neutron stars accreting from the interstellar medium and ‘anomalons X-ray pulsars’ (van Paradijs et al. 1995) with periods of a few seconds and large X-ray luminosities relative to the power available from their spin down. The latter objects are thought to be isolated neutron stars powering their X-radiation by accretion and to result from a high mass X-ray binary (HMXB) which underwent a common envelope phase (van Paradijs et al. 1995, Ghosh et al. 1997). The distances and ages of the four examples known give a total of only 20–50 such pulsars in the Galaxy, a very low number appropriate for their exotic history. Therefore, although these objects are difficult to distinguish from other pulsars without the detection of pulsations and are radio-quiet, it is unlikely that they explain all the candi-
Figure 1. The luminosities of radio pulsars at 400 MHz (top) and 1.4 GHz (bottom) against spin-down power. Larger symbols indicate pulsars at distances of less than 3.5 kpc. Restrictive upper limits are included for Geminga and the X-ray-selected candidate neutron stars selected from Table 1. Dashed horizontal lines illustrate a luminosity of 1 mJy kpc$^2$.

Empirically, the underlying luminosity function of nearby radio pulsars flattens below 20 mJy kpc$^2$ (Lyne et al. 1997), giving no evidence for substantial numbers of low luminosity pulsars. In addition, proposing that the candidate pulsars...
Figure 2. The luminosities of radio pulsars and candidate neutron stars at 400 MHz (top) and 1.4 GHz (bottom) against pulsar or SNR age, where pulsar ages are calculated from $\tau = p/2\dot{p}$ and SNR ages are listed in Table 1. Larger symbols show the positions of pulsars with distances of less than 3.5 kpc.

have low radio luminosities or steep spectra leads to a conflict with such population constraints, unless there is some mechanism that can suppress the radio emission from young pulsars but permits high energy radiation and the formation of plerions. This is a particular problem for the candidates in young SNRs, since we would expect large numbers of similar objects at greater ages.

It has previously been proposed that pulsars with extreme parameters, such as unusually long periods or high magnetic fields, might have radio luminosities low enough
to escape detection. For example, slow ($P > 0.3$ s) pulsars with low magnetic fields might be ‘injected’ into the population, forming a sub-population of low luminosity pulsars (Narayan 1987). However, there is no compelling observational evidence for injected pulsars. A number of authors have now shown that the results of radio pulsar surveys and the small number of pulsar/SNR associations can be explained at least as well by a simple, single population as by multi-population models (Bhattacharya et al. 1992, Frail & Moffett 1993, Lorimer et al. 1993, Gaensler & Johnston 1995, Lorimer et al. 1997b).

The simplest explanation for the candidate radio-quiet pulsars is that they are radio pulsars whose beams do not sweep past the Earth. This requires no new population of neutron stars and can accommodate all of the candidates and Geminga. However, it has a number of implications for pulsar beaming and pulsar statistics, discussed below.

### 3.1 Beaming

Pulsars are complex X-ray sources. The very young, Crab-like radio pulsars are visible in soft X-rays as non-thermal, highly pulsed, compact sources surrounded by a bright nebula of synchrotron X-rays. Older pulsars, up to a few $\times 10^{5}$ years old, are generally much weaker point sources and usually lack a synchrotron nebula. In these pulsars, the non-thermal pulses become dominant only above a few keV, while the X-rays in the ROSAT (0.1 – 2.4 keV) band are thermal radiation from the $10^{6}$ K neutron star surface, representing the cooling of the hot stellar interior and bombarding of the polar caps by fast particles from the magnetosphere. The polar caps of the neutron star are hotter than the rest of the surface and are detected as pulses, but because the radiation is bent gravitationally, the pulses are spread out to give a low degree of modulation even when radiation is entirely from the polar caps (Zavlin et al. 1995, Page 1995, Yancopoulos et al. 1994). Typically less than 20% of the keV flux in detected pulsars forms the characteristically broad, smooth pulse, in agreement with the predictions. We will therefore assume that this thermal radiation is spread by gravitational bending to be visible from all directions. This means that our ability to detect a neutron star from its soft X-ray emission is unaffected by beaming.

Thermal emission appears to be responsible for the X-rays from the candidate neutron stars, given their low luminosities, soft spectra and the lack of pulsations below 2 keV. Where the spectra have been modelled, they have been described as blackbody, although not all of them are well constrained.

The beaming fraction of radio pulsars is not well known. It is generally accepted that the average beaming fraction for the whole population is around 20% (e.g. Lyne & Manchester 1988). Taurus & Manchester (1997) find that it is only 10% but anti-correlates with age, giving a much higher beaming fraction for young pulsars. Some authors (e.g. Narayan 1987) find a beaming fraction approaching 100% for young pulsars, boosting their case for injection of long-period pulsars into the population. Frail & Moffett (1993) derived a value of 61 ± 13% from a deep search for (young) radio pulsars in plerions.

We can provide an independent measure of the beaming fraction by considering the pulsars which have been detected in X-rays but are radio-quiet. Taking just the pulsar candidates with quantitative radio flux limits, the six in SNRs have ages less than 20,000 yr and distances smaller than 3.5 kpc. Six known radio pulsars also satisfy these criteria: PSRs B0531+21, B0833–45, B1706–44 and B1046–58, all of which have been detected at high energies, and PSRs B1737–30 and B1853+01, which have not. These latter two pulsars are relatively low down on the $E/d^2$ ranking, probably explaining why they have not been detected. The number of radio-quiet pulsars relative to the total yields a radio beaming fraction of $\sim 50%$ for young pulsars, assuming that the sample is largely complete. We argue below that this is the case. The radio-quiet pulsars are clearly inconsistent with beaming fractions close to 100%.

#### 3.1.1 Geminga-like $\gamma$–ray pulsars

The presence of pulsed $\gamma$-rays from a radio-quiet pulsar allows us to constrain the emission geometry of the radio and high energy beams. At present $\gamma$-ray pulses have been identified only in Geminga, although the candidate pulsars RXJ0007.0+7302 and RXJ2020.2+4026 are also coincident with $\gamma$-ray sources. The beaming explanation for radio-quiet neutron stars therefore demands a model in which it is possible to see the hard X/$\gamma$-ray pulses without intersecting the radio beam.

Current data on the high energy emission from pulsars is limited by the sensitivity of available instruments. In $\gamma$-rays, just six radio pulsars have been detected as pulsed sources (Thompson et al. 1994, Ramanamurthy et al. 1995, Carramiñana et al. 1995). The range of pulse shapes, from a single broad hump to two widely separated, sharp peaks connected by a saddle, can be explained in terms of different lines of sight across a single, edge-brightened beam (Daugherty & Harding 1996, Romani & Yadigaroglu 1995). The wide pulses imply a broad beam unless there are only small offsets between the observer, the beam axis and the neutron star spin axis. Wider beams are generally preferable because they do not require such a specific geometry and can explain why all of the radio pulsars with highest $E/d^2$ have been detected.

In order to explain radio-quiet pulsars by beaming, the high energy and radio beams cannot be generated in the same location in the neutron star magnetosphere. One possibility (e.g. Romani & Yadigaroglu 1995) is that the high energy beams are produced near the light cylinder (co-rotation radius) while the radio is beamed along the magnetic axis. Efficient production of high energy photons in this model depends on a high inclination of the magnetic axis (Romani 1996) and a pulsar with low magnetic inclination or viewed from near the spin axis would not be visible at high energies. Approximately two-thirds of the pulsars visible as EGRET $\gamma$-ray sources would be radio-quiet in this model (Yadigaroglu & Romani 1995), although a larger radio beaming fraction and allowance for deep, targeted radio pulsar searches will decrease this figure. Several groups are working on unidentified $\gamma$-ray sources to look for radio-quiet pulsars.

Uncertainty over the inclinations measured from radio polarisation (Lyne & Manchester 1988, Rankin 1990, Manchester 1996) fuels an on-going debate between the above model and an alternative set of models with exactly the opposite geometric requirements (Daugherty & Harding...
1996, Sturner & Dermer 1995). These ‘polar cap’ models have been successful in explaining the spectra and γ–ray luminosities of radio pulsars, but they require that the pulsar magnetic and spin axes are approximately aligned in order for the emission from a single magnetic pole to produce the broad observed pulses. The most recent simulations (Daugherty & Harding 1996) have more relaxed geometries than earlier models. If polar cap models are to explain radio-quiet pulsars by beaming, then the radio beams come either from a separate region of the magnetosphere or are internal to the hollow γ–ray cone. The radio pulses of γ–ray pulsars are (so far) always outside the γ–ray pulse, inconsistent with an internal radio beam (Daugherty & Harding 1996). In both outer gap and polar cap models, therefore, the radio and high energy beams of radio-quiet pulsars must be generated in different parts of the magnetosphere.

3.2 The pulsar birth rate

Pulsar birth rates are usually derived from observations and models of the radio population alone. In this section we use the X-ray observations of young neutron stars, usually neglected in such calculations, to constrain the local pulsar birth rate independent of radio beaming and luminosity laws.

As we listed in Section 3.1, 10 neutron stars with ages less than 20,000 years and distances below 3.5 kpc have been detected in X-rays. This implies a birth rate of 13 Myr$^{-1}$ kpc$^{-2}$, if pulsars are born close to the Galactic disk and the X-rays are not beamed. In order to extrapolate this to the whole Galaxy, we assume that the radial distribution of pulsars is a Gaussian with a radial scale length of 5 kpc (e.g. Lorimer et al. 1993), which gives a Galactic neutron star birth rate of 1 every 110 years. Adding two radio pulsars that have not yet been detected in X-rays raises this figure to 1 every 91 years. Further allowance for incompleteness in the X-ray detections can only increase the birth rate further.

The frequency of supernova explosions and the birthrates of SNRs and pulsars have been the subject of discussion since the late 1960’s. Recent calculations give a total (Type I plus Type II) Galactic supernova rate of 1 every 40 years (Tammann et al. 1994), similar to the rate of one Type II every 50–170 years derived from extragalactic supernova searches (Cappellaro et al. 1997). A recent estimate for the birth rate of radio pulsars is 1 every 60 – 330 years (Lyne 1997). Gaensler & Johnston (1995) found that a birth rate of one every 85 years gave an excellent match between observed and modelled SNR/pulsar associations.

The birth rate cannot be a factor of 2 higher than we have derived from the X-ray neutron star population, or it will be in conflict with the (independently derived) supernova rate. It is also unlikely to be much lower than our estimate because our sample is not complete. The birth rates for neutron stars, Type II supernovae and radio pulsars are therefore similar. We conclude that (a) probably all young neutron stars are radio pulsars, (b) more young pulsars are visible as X-ray sources than as radio pulsars, and (c) most of the young, nearby pulsars have already been discovered.

Lastly, our result supports the conclusion of Gaensler & Johnston (1995) that the small number of known pulsar/SNR associations is a consequence of pulsar beaming and luminosity, not a dearth of radio pulsars.

4 CONCLUSIONS

This paper has clarified the evidence for radio-quiet pulsars and the implications of such objects. We have listed six clear, unresolved X–ray sources in supernova remnants, with quantitative radio flux limits and high X–ray to optical flux ratios that rule out nearly all types of X–ray source. Most of them are the only X–ray point source within their SNR and they are all close to their SNR centres, making a strong case that they are stellar remnants associated with the SNRs. Their transverse velocities are consistent with the velocities observed in radio pulsars (Frail et al. 1994, Lorimer et al. 1997a). We find that it is simplest to explain all of these objects, plus two further objects without SNRs, as neutron stars.

The candidate neutron stars have lower radio fluxes than would be expected from known radio pulsars of equivalent age or spin-down power. Reasons for this might include extreme spin parameters (e.g. because of large magnetic fields) or truly low radio luminosities. However, these are not necessary to explain the sources or justified by other empirical evidence. The low radio luminosities are most simply accommodated in a geometric explanation, in which the radio emission is not favourably beamed whereas the soft X–rays are dominated by thermal emission from the neutron star surface and are visible from all directions. The relative numbers of radio pulsars and X–pulsar candidates in SNRs gives a crude estimate of ~ 50% for the radio beaming fraction.

Above ~ 2 keV, non-thermal emission from the magnetosphere becomes dominant in known pulsars. The presence of high energy radiation without radio pulses implies different emission sites for the two ends of the spectrum. The candidate pulsars in CTA 1 and G078.2+2.1 coincide with γ–ray sources and searches for pulsations in the high energy fluxes should be pursued. 1E 1207.4–5209, the candidate neutron star in G296.5+10.0, has not shown any evidence for magnetospheric emission. This could mean that the object is a cooling neutron star with only weak magnetospheric activity (Vasisht et al. 1997), but it could also be a pulsar in which both the radio and high energy beams are directed away from the Earth. The object’s rotation frequency may still be discovered from low-level modulations of the thermal soft X–rays.

We have also used the assumption of quasi-isotropic X–ray emission to estimate the neutron star birth rate, which we find to be at least 13 Myr$^{-1}$ kpc$^{-2}$ in the neighbourhood of the Sun. The total galactic birth rate is therefore at least 1 neutron star every ~ 90 years, close to the derived rate of Type II supernovae (Cappellaro et al. 1997). We conclude that neutron stars are a frequent outcome of supernovae, that probably all neutron stars are born as radio pulsar and that most young, nearby pulsars have already been discovered. This is further support for our result that radio-quiet pulsars are best explained as unfavourably beamed radio pulsars.

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6 REFERENCES

Becker R.H., Helfand D.J., Szymkowiak A.E., 1982, ApJ, 255, 557
Bertsch D.L., et al., 1992, Nature, 357, 306
Blattacharya D., 1990, J.Astrophys.Astr., 11, 125
Blattacharya D., Wijers R., Hartman J.W., Verbunt F., 1992, A&A, 254, 198
Brazier K.T.S., Kanbach G., Carramiñana A., Guichard J., Merck M., 1996, MNRRAS, 281, 1033
Brazier K.T.S., Reimer O., Kanbach G., Carramiñana A., 1997, in press
Campana S., Mereghetti S., Sidoli L., 1997, A&A, 320, 783
Cappellaro E., Turatto M., Tsvetkov D.Yu., Bartunov O.S., Pollas C., Evans R., Hamuy M., 1997, A&A, 322, 431
Carramiñana A., et al., 1995, A&A, 304, 258
Caraveo P.A., Bignami G.F., Mignani R., Taff L.G., 1996, ApJ, 461, L91
Clark D.H., Stephenson F.R., 1977, 'The Historical Supernovae', (Pergamon)
Daugherty J.K., Harding A.K., 1996, ApJ, 458, 278
Esposito J.A., Hunter S.D., Kanbach G., Sreekumar P., 1996, ApJ, 461, 820
Gaensler B.M., Johnston S., 1995, MNRAS, 277, 1243
Green D.A., 1996, "A catalogue of Galactic Supernova Remnants (1996 August version", Mullard Radio Astronomy Observatory, Cambridge, UK; available at http://www.mrao.cam.ac.uk/surveys/snrs/index.html
Gregory P.C., Fahlman G.G., 1980, Nature, 287, 805
Hailey C.J., Craig W.W., 1995, ApJ, 455, L151
Halpern J.P., Ruderman M., 1993, ApJ, 415, 286
Helfand D.J., Becker R.H., White R.L., 1995, ApJ, 453, 741
Kaspi V.M., 1996, in "Pulsars: Problems and Progress", proc. IAU Colloq. 160, eds. Johnston S., Walker M.A., Bailes M., submitted to MNRAS
Kaspi V.M., Manchester R.N., Johnston S., Walker M.A., 1995, ApJ, 476, L43
Kaspi V.M., Manchester R.N., Lyne A.G., D’Amico N., 1996, AJ, 111, 2028
Kellett B.J., Branduardi-Raymont G., Culhane J.L., Mason I.M., Mason K.O., Whitehouse D.R., 1987, MNRRAS, 229, 199
Kuzmin A.D., Losovsky B.Y., 1997, Pis’ma Astron. Zh., 23, 323
Lorimer D.R., Bailes M., Dewey R.J., Harrison P.A., 1993, MNRRAS, 263, 403
Lorimer D.R., Bailes M., Harrison P.A., 1997a, MNRRAS, 289, 592
Lorimer D.R., Lyne A.G., Camilo F., 1997b, submitted to A&A
Lyne A.G., Manchester R.N., Taylor J.H., 1985, MNRRAS, 213, 613
Lyne A.G., Manchester R.N., 1988, MNRRAS, 234, 477
Lyne A.G., et al., 1997, MNRRAS, in press
Malofeev V.M., Malov O.I., 1997, Nature, 389, 697
Manchester R.N., 1996, in "Pulsars: Problems and Progress", proc. IAU Colloq. 160, eds. Johnston S., Walker M.A., Bailes M. (PASP), p194
Manning R.A., Jeffries R.D., Willmore A.D., 1996, MNRRAS, 278, 577
Matsui Y., Long K.S., Tuohy I.R., 1988, ApJ, 329, 838
Narayan R., 1987, ApJ, 319, 162
Neuhäuser R., Thomas H.-C., Danner R., Peschke S., Walter F.M., 1997, A&A, 318, L43
Ögelman H., 1995, in “The Lives of the Neutron Stars”, eds Alpar A., Kilizóglu U, van Paradijs J. (Kluwer, Dordrecht), p101
Page D., 1995, ApJ, 442, 273
Petre R., Cauzaires C.R., Kriss G.A., Winkler P.F., Jr., 1982, ApJ, 258, 22
Petre R., Okada K., Mihara T., Makishima K., Colbert E., 1994, PASJ, 46, L115
Petre R., Becker C.M., Winkler P.F., 1996, ApJ, 465, L43
Pineault S., Landecker T.L., Madore B., Gaumont-Guay S., 1993, AJ, 105, 1060
Ramanamurthy P.V., et al., 1995, ApJ, 477, L109
Rankin J.M., 1990, ApJ, 352, 247
Romani R.W., Yadigaroglu I.-A., 1995, ApJ, 438, 314
Romani R.W., 1996, ApJ, 470, 469
Schwentker, O., 1994, A&A, 286, L47
Seiradakis J., 1992, IAU Circ. 5532
Seward F.D., Wang Z.-R., 1988, ApJ, 332, 199
Slane P., Seward F.D., Bandiera R., Torii K., Tsunemi H., 1997, ApJ, 485, 221
Stocke J.T., Wang Q.D., Perlman E.S., Donahue M.E., Schachter J., 1995, AJ, 109, 1199
Sturmer S., Dermer C.D., 1995, A&A, 293, L17
Tammann G.A., Loewf W., Schroeder A., 1994, ApJS, 92, 487
Tauris T.M., Manchester R.N., 1997, submitted to MNRRAS
Taylor, J.H., Stinebring D.R., 1986, ARA&A, 24, 285
Taylor J.H., Manchester R.N., Lyne A.G., 1993, ApJS, 88, 529; updated (1996) version available by anonymous ftp from pulsar.princeton.edu
Thompson D.J., et al., 1994, ApJ, 436, 229
Tuohy I.R., Carmine G.P., 1980, ApJ, 239, L107
van Paradijs J., Taam R.E., van den Heuvel E.P.J., 1995, A&A, 291, L41
Vasisht G., Gotthelf E.V., 1997, ApJ, 486, L129
Vasisht G., Kulkarni S.R., Anderson S.B., Hamilton T.T., Kawai N., 1997, ApJ, 476, L43
Walker F.M., Seward F.D., Wang Z.-R., Lin J.Y., Gorenstein P., Zombeck M.V., 1986, Highlights of Astronomy, 7, 583
Yadigaroglu I.-A., Romani R.W., 1995, ApJ, 449, 211
Yancopoulos S., Hamilton T.T., 1995, AJ, 109, 2442
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