The implications of radio-quiet neutron stars

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Accepted 1999 January 8. Received 1998 December 23; in original form 1997 October 30

ABSTRACT
We collate the evidence for rotation-powered neutron stars that are visible as X-ray sources and not as radio pulsars. To date, 10 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 γ-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 (t < 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 10 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. A simple explanation within the context of existing 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 thermal surface 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 γ-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 numbers of candidate neutron stars and radio pulsars younger than 20 000 yr and within 3.5 kpc, the radio beaming fraction of young pulsars is estimated to be roughly 50 per cent and certainly much less than 100 per cent. 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 ~90 yr. 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 – X-rays: stars.

1 INTRODUCTION
The Princeton pulsar catalogue (Taylor, Manchester & Lyne 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- or 1400-MHz flux: the X- and γ-ray pulsar known as Geminga (Bertsch et al. 1992; Halpern & Holt 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 ~20 other pulsars in the Princeton catalogue that have been detected as X-ray sources. Seven, including Geminga, have also been seen by γ-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, E, so that 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 E/d2 ≥ 1034 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

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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 disc.

Geminga is a 350 000-year-old pulsar at a distance of only ~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 neutron star as a rotation-powered neutron star 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 neutron stars 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 neutron star is usually an extreme spectrum: bright in X-rays and/or γ-rays but very faint at optical wavelengths. While Geminga is the sole confirmed radio-quiet pulsar, nine further objects seen as unresolved X-ray sources have been proposed as radio-quiet, rotation-powered neutron stars after fulfilling the first criteria for detection of a pulsar. In this paper, we add these to Geminga to examine the case for radio-quiet neutron stars as a class and to distinguish between beaming and luminosity explanations for these objects.

### 2 THE CANDIDATE NEUTRON STARS

Nine objects that have previously been proposed as radio-quiet neutron stars are listed in Table 1, together with Geminga. Each of the candidates is an unresolved X-ray source that has not been associated with a compact radio object. Seven of the objects are within supernova remnants (SNRs). Beyond these generalities, the sources and the work done to identify them are varied. In Section 2.1, below, we summarize the evidence that has been presented in support of the case that each of them is a radio-quiet neutron star. We do not include in this paper the ‘anomalous X-ray pulsars’ – e.g., 1E 2259+586, RX J1838.4–0301 and 1E 1841–045 (Gregory & Fahlman 1980; Schwentker 1994; Vasisht & Gotthelf 1997) – which are thought to be isolated but powered by accretion from a residual disc (van Paradijs, Taam & van den Heuvel 1995).

The X-ray fluxes listed in Table 1 provide a useful way to estimate the spin-down power $E$ of the candidates. Older radio pulsars detected as point X-ray sources follow an approximate trend of $L_x \sim 3 \times 10^{-4} \dot{E}$ (cf. Seward & Wang 1988; Ögelman 1995), which we can invert to estimate the spin-down power. Since the trend includes only the detected X-ray pulsars, it is biased towards high X-ray luminosities, and an $E$ derived from it may be underestimated. No allowance for the bias is made in this paper, because the candidates are also selected as X-ray sources, but it remains an uncertainty.

The plerions in 3C 58 and CTA 1 provide an independent way to estimate the power of the embedded objects. 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. Slane et al. (1997) used this relationship for CTA 1 to estimate a spin-down power of $1.7 \times 10^{36} \text{erg s}^{-1}$. For 3C 58, similar considerations of the X-ray synchrotron emission yield $E = (2-4) \times 10^{36} \text{erg s}^{-1}$ (Helfand, Berker & White 1995), while $E = 1.5 \times 10^{36} \text{erg s}^{-1}$ is required to explain a radio filament near to the candidate neutron star in terms of a shock in a pulsar wind (Frail & Moffett 1993).

Coincidence with a γ-ray source provides a third way to estimate the spin-down power. While the relationship between γ-ray luminosity and spin-down power is still unclear (Fierro 1995), Brazier et al. (1996, 1998) showed that the γ-ray luminosities inferred for the candidates in CTA 1 and G078.2+2.1 were consistent with those of the Vela pulsar 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 γ-ray comparison would suggest. The estimates from the γ-ray fluxes are listed in Table 1. An intermediate spin-down power is used in this paper for these two objects.

In addition to the candidate neutron stars within SNRs, 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 an SNR, it is also difficult to estimate the distances to these objects or to guess their ages. Nevertheless, the one confirmed radio-quiet pulsar is in this group.

<table>
<thead>
<tr>
<th>Name</th>
<th>$F_X$ (0.1–2.4 keV) (erg cm$^{-2}$ s$^{-1}$)</th>
<th>$E$ (10$^{30}$ erg s$^{-1}$)</th>
<th>$S_{200}$ (mJy)</th>
<th>$S_{1400}$ (mJy)</th>
<th>SNR name</th>
<th>Common name</th>
<th>dist (kpc)</th>
<th>age (10$^3$ yr)</th>
<th>refs</th>
</tr>
</thead>
<tbody>
<tr>
<td>RX J0002+6246</td>
<td>$2 \times 10^{-13}$</td>
<td>$&lt;4$</td>
<td>?</td>
<td>?</td>
<td>G117.7+0.6</td>
<td>CTA1</td>
<td>3</td>
<td>20</td>
<td>1,2</td>
</tr>
<tr>
<td>RX J0007.0+7302</td>
<td>$9 \times 10^{-14}$</td>
<td>$5 \times 10^6$</td>
<td>$&lt;1.5$</td>
<td>$&lt;0.3$</td>
<td>G119.5+10.2</td>
<td>CTA1</td>
<td>1.4</td>
<td>5–10</td>
<td>3,4</td>
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<tr>
<td>RX J2021.8+6435</td>
<td>?</td>
<td>$2 \times 10^6$</td>
<td>$&lt;2.1$</td>
<td>$&lt;0.15$</td>
<td>G130.7+3.1</td>
<td>3C 58</td>
<td>3.2</td>
<td>0.8</td>
<td>6,7</td>
</tr>
<tr>
<td>IE 0820–4247</td>
<td>$3 \times 10^{-12}$</td>
<td>$1.7 \times 10^6$</td>
<td>$&lt;1.0$</td>
<td>$&lt;0.3$</td>
<td>G260.4–3.4</td>
<td>Pup A</td>
<td>2</td>
<td>3.7</td>
<td>8,9</td>
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<tr>
<td>IE 1207.4–5209</td>
<td>$2 \times 10^{-12}$</td>
<td>$1.0$</td>
<td>$&lt;1.0$</td>
<td>$&lt;0.3$</td>
<td>G296.5+10.0</td>
<td>PKS 1209–51/52</td>
<td>1.5</td>
<td>7</td>
<td>10,11</td>
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<td>IE 161348–5055</td>
<td>$7 \times 10^{-13}$</td>
<td>$&lt;1.5$</td>
<td>$&lt;1.0$</td>
<td>$&lt;0.1$</td>
<td>G332.4–0.4</td>
<td>RCW103</td>
<td>3.3</td>
<td>1–3</td>
<td>12,13,10</td>
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<tr>
<td>RX J2020.2+4206</td>
<td>$4 \times 10^{-14}$</td>
<td>$7 \times 10^6$</td>
<td>$&lt;5$</td>
<td>$&lt;0.35$</td>
<td>G078.2+2.1</td>
<td>–Cyg</td>
<td>1.5</td>
<td>10</td>
<td>14,5</td>
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<tr>
<td>– cases with no SNR – Geminga</td>
<td>$4 \times 10^{-11}$</td>
<td>$3 \times 10^4$</td>
<td>$&lt;0.1$</td>
<td>$&lt;1.0$</td>
<td></td>
<td></td>
<td>0.16</td>
<td>350</td>
<td>15</td>
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<tr>
<td>RX J1856.5–3754</td>
<td>$1 \times 10^{-11}$</td>
<td>$&lt;4$</td>
<td>?</td>
<td>?</td>
<td></td>
<td></td>
<td>0.12</td>
<td>16,17</td>
<td></td>
</tr>
<tr>
<td>MS 0317–6647</td>
<td>$4 \times 10^{-13}$</td>
<td>$&lt;4$</td>
<td>?</td>
<td>?</td>
<td></td>
<td></td>
<td></td>
<td>18</td>
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</table>
2.1 Candidate neutron stars within SNRs

2.1.1 RX J0002+6246 (G 117.7+0.6)

G 117.7+0.6 is a faint X-ray arc discovered in ROSAT PSPC images by Hailey & Craig (1995), and is proposed to form part of a previously unknown shell-type SNR at a distance of ~3 kpc. An unidentified point source, RX J0002+6246, is clearly visible 10 arcmin from the central position. With no plausible counterpart among the nearby optical sources and no catalogued radio source at this position, it was suggested that RX J0002+6246 could be a radio-quiet neutron star associated with the proposed remnant, possibly with a pulsation period of 242 ms (Hailey & Craig 1995).

G 117.7+0.6 has not been the subject of any targeted search for a radio pulsar. However, the area was covered by the large-scale surveys performed by Stokes et al. (1986) and Sayer, Nice & Taylor (1997) with the Green Bank telescope. Their observing frequencies were 370 and 390 MHz respectively, and they quote sensitivities to long-period pulsars of 4 and 8 mJy. Combined with the proposed distance of 3 kpc, these are not restrictive limits; RX J0002+6246 is not included in this paper as a radio-quiet neutron star candidate.

2.1.2 RX J0007.0+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 RX J0007.0+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. 1998). The flux and spectrum of a persistent, unidentified γ-ray source coincident with RX J0007.0+7302 are consistent with emission from a pulsar at the age and distance of CTA 1, leading Brazier et al. (1998) 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 RX J2020.2+4026 (3C 58)

3C 58 (G 130.7+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 Ab 1181 (Clark & Stephenson 1977). The nebula spectrum breaks at a much lower frequency than in the Crab, suggesting that the magnetic field must be high. If this reflects the field of an embedded neutron star, it might also explain the rapid secular decline in electron injection postulated to explain the sharpness of the break (Woltjer et al. 1997). Confirmation that there is indeed a compact X-ray source within the pleron (Becker, Heffland & Szynkowiak 1982) was provided by Helfand et al. (1995). It is still unclear whether a north-south ellipticity of the X-ray source is due to attitude reconstruction problems known to affect some ROSAT data or whether it means that the object is in fact associated with a radio filament discovered by Frail & Moffett (1993). Helfand et al. (1995) determined that the X-ray luminosity of the plerionic SNR emission is \((4-7) \times 10^{33} \text{ erg s}^{-1}\), which would require the neutron star to have a spin-down power of \(E_s \sim (0.1 \text{ to } -4) \times 10^{35} \text{ erg s}^{-1}\), 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 per cent 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 has 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, Becker & Winkler 1996). Stringent optical and radio limits (Kaspi et al. 1996; Petre et al. 1996) rule out most types of X-ray source, 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 per cent 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 (G 296.5+10.0)

G 296.5+10.0 has a symmetric ‘barrel’ morphology defined by two clear, elongated radio arcs; its age is estimated to be roughly 20000 yr (Seward & Wang 1988). Using Einstein observations of the remnant, Kellett et al. (1987) showed 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, Long & Tuohy (1988) and Meremegheti, Bignami & Caraveo (1996) have published further details of the effort to identify this X-ray source. They find no plausible optical counterpart down to \(m_{\text{V}} \sim 25\) and place a 0.1-mJy limit at 4.8 GHz. Kaspi et al. (1996) place a tighter, 1-mJy limit on pulsations at 436 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 25 per cent of the ASCA flux is pulsed.

2.1.6 1E 1613−5055 (RCW 103)

Einstein HRI observations first revealed an unresolved X-ray source, IE 161348 − 5055, 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 436-MHz and 1.5-GHz pulsed flux density limits of 1.5 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 (Gottthelf, Petre & Hwang 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 1000–3000 yr; the supernova responsible for RCW 103 may have been a guest star reported in 134 bc (Wang et al. 1986).

2.1.7 RX J2020.2+4026 (G 078.2+2.1)

The γ-ray source 2EG J2020+4026 (2CG 078) has been linked with the G 078.2+2.1 SNR by several authors, most recently Sturmer &
Dermer (1995) and Esposito et al. (1996). During a detailed study of the γ-ray source, Brazier et al. (1996) noted the existence of a single unresolved X-ray source, RX J2020.2+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 γ-ray fluxes are from a pulsar in the G 078.2+2.1 SNR. Like RX J0007.0+7302, the proposed pulsar is Vela-like, with a small X-ray flux relative to the γ-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 γ-rays (Bertsch et al. 1992), confirmed this as a pulsar, albeit one with an inferred 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 the higher frequencies used in this paper.

The lack of absorption of Geminga’s X-ray flux and its high γ-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 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, Stocke 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). In the absence of information on the distance to MS 0317–6647, it is difficult to assess this possibility, and unless the distance is less than 100 pc, the pulsed 400-MHz limit of 4 mJy (Lyne et al. 1998) is not restrictive for an older pulsar. The object is not included further in this paper.

2.2.3 RX J1856.5–3754

RX J1856.5–3754 was first detected in the Einstein slew survey, is a very bright, unidentified X-ray source, and does not vary. Walter, Wolk & Neuhauser (1996) proposed that the low NH measured from the X-ray spectrum implied that the object lay in front of a molecular cloud in the line of sight at ~120 pc. They concluded that the object was a nearby, old neutron star, perhaps powering its X-ray emission through accretion from the ISM.

Reassessments of RX J1856.5–3754 published by Campana, Mereghetti & Sidoli (1997) and Neuhauser et al. (1997) both confirm this conclusion, and Walter & Matthews (1997) have now identified a faint optical counterpart at magnitude 25.6, consistent with 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. The distance may be larger than claimed by Walter et al. (1996). Although the X-ray spectrum is well modelled by blackbody radiation from the surface of a neutron star at 100–170 pc, the X-ray spectra of known radio pulsars do not give reliable distances under the same assumptions. Observations of the parallax and/or proper motion of RX J1856.5–3754 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 10 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 SNRs 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 3C 58, 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, Goss & Whiteoak 1994) and the median of 300 km s⁻¹ seen in the general population of radio pulsars (Lorimer, Bailes & Harrison 1997). Also listed in Table 2 is the angular distance β between the candidate neutron star and the SNR centre, expressed as a fraction of the SNR radius. The values of β here are smaller than in most suggested associations between radio pulsars and SNRs (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 3C 58 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 SNRs, 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.
star. For the remainder of this paper, it will be assumed that all eight candidates are neutron stars.

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 they be normal radio pulsars? 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 candidate neutron stars. The figures demonstrate the rise towards a higher median luminosity for energetic pulsars, ≈300 mJy kpc$^{-2}$ at 400 MHz, ≈100 mJy kpc$^{-2}$ at 1400 MHz (e.g. Lyne, Manchester & Taylor 1985; Taylor & Stinebring 1986; Tauris & Manchester 1998) and the sensitivity limits of radio searches. Using Table 1, the upper limits for the seven candidates and Geminga have also been added. Each of the candidates 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.

A similar picture is obtained when the radio luminosities are plotted against pulsar/candidate age, as shown in Fig. 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. However, increasing the distances in both Figs 1 and 2 would make the radio limits weaker, and the candidate neutron stars therefore 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 are pulsars with small intrinsic radio luminosities or very steep radio spectra.

(2) They are pulsars whose radio beams are directed away from Earth.

(3) They are pulsars with unusual spin parameters untested by current pulsar searches.

(4) They are not rotation-powered neutron stars.

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 powered by rotation until each of them has been identified conclusively. Weak accretion has been suggested as a possible power source in RX J1856.5–3754 and 1E 1207.4–5209. The accretion models fall into two types: old neutron stars accreting from the ISM, and `anomalous 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, Angellini & White 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 candidate neutron stars. Old neutron stars producing detectable X-ray fluxes by accretion from the ISM must also be rare, because deep searches have failed to find any (Manning, Jeffries & Willmore 1996; Danner 1998a,b). This mechanism is a proposed explanation for only one of the candidates, RX J1856.5–3754.

Empirically, the underlying luminosity function of nearby radio pulsars flattens below 20 mJy kpc$^{-2}$ (Lyne et al. 1998), giving no evidence for substantial numbers of low-luminosity pulsars. Proposing that the candidate neutron stars are pulsars with 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 subpopulation of low-luminosity pulsars (Narayan 1987). However, there is no compelling observational evidence for injected pulsars, and 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 multipopulation models (Bhattacharya et al. 1992; Frail & Moffett 1993; Lorimer et al. 1993; Gaensler & Johnston 1995; Lorimer, Lyne & Camilo 1998).

The simplest explanation for the candidate radio-quiet neutron stars 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 mainly thermal radiation from the $10^6$ K neutron star surface. The polar caps of the neutron star, the hottest parts of the surface, are detected as pulses, but gravitational bending of this radiation keeps the degree of modulation low even when radiation is entirely from the polar caps (Yancopoulos, Hamilton & Heßland 1994; Page 1995; Zavlin, Shibanov & Pavlov 1995). Typically, less than 20 per cent 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 has been broadened gravitationally and is visible from all directions. This means that our ability to detect a neutron star from its soft X-ray emission is essentially 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. Tauris & Manchester (1998) find that the average beaming fraction is only 10 per cent but anticorrelates with age, giving a much higher beaming...
fraction for young pulsars. Frail & Moffett (1993) estimate that the beaming fraction for young pulsars is $61 \pm 13$ per cent, based on observations of the number of radio plerions with and without associated pulsars.

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. Of our eight candidates, 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 $\sim 50$ per cent for young pulsars, assuming that the sample is largely complete. We argue below that this is the case.

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$^{-2}$.
The radio-quiet pulsars are clearly inconsistent with beaming fractions close to 100 per cent.

3.1.1 Geminga-like γ-ray pulsars

The presence of pulsed γ-rays from a radio-quiet pulsar allows us to constrain the emission geometry of the radio and high-energy beams. At present γ-ray pulses have been identified only in Geminga, although the candidate pulsars RX J0007.0+7302 and RX J2020.2+4026 are also coincident with γ-ray sources. The beaming explanation for radio-quiet neutron stars therefore demands a model in which it is possible to see the hard X-/γ-ray pulses without intersecting the radio beam.

Current data on the high-energy emission from pulsars are limited by the sensitivity of available instruments. In γ-rays, just six radio pulsars have been detected as pulsed sources (Thompson et al. 1994; Carramiñana et al. 1995; Ramanamurthy et al. 1995). The range of pulse shapes, from a single broad hump to two widely

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 $\tau = p/2\pi$ and SNR ages are listed in Table 1. Larger symbols show the positions of pulsars with distances of less than 3.5 kpc.
separated, sharp peaks connected by a saddle, can be explained in terms of different lines of sight across a single, edge-brightened beam (Romani & Yadigaroglu 1995; Daugherty & Harding 1996). 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 more easily why all of the radio pulsars with highest $E_{\gamma}$ 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 (corotation 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); 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 model above and an alternative set of models with exactly the opposite geometric requirements (Sturmer & Dermer 1995; Daugherty & Harding 1996). These ‘polar cap’ models have been successful in explaining the spectra and $\gamma$-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. 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 either come from a separate region of the magnetosphere or are internal to the hollow $\gamma$-ray cone. The radio pulses of $\gamma$-ray pulsars are (so far) always outside the $\gamma$-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 largely independently of radio beaming and luminosity laws.

A total of 10 neutron stars with ages less than 20 000 yr and distances below 3.5 kpc have been detected in X-rays. These include six objects from Table 1 and four radio pulsars listed in Section 3.1. This implies a birth rate of $13 \text{Myr}^{-1}$ kpc$^{-2}$, if pulsars are born close to the Galactic disc 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 scalelength 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 1960s. Recent calculations give a total (Type I plus Type II) Galactic supernova rate of 1 every 40 years (Tammann, Loeffler & Schroeder 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 et al. 1998). 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 unresolved X-ray 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. 1997). 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-ray pulsar candidates in SNRs gives a crude estimate of $\sim50$ per cent for the radio beaming fraction.

Above $\sim2\text{keV}$, 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 G 078.2+2.1 coincide with $\gamma$-ray sources and searches for pulsations in the high-energy fluxes should be pursued. 1E 1207.4–5209, the candidate neutron star in G 296.5+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 pulsars, 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.

ACKNOWLEDGMENTS

We thank Bryan Gaensler for his constructive reading of this paper. KTSB thanks the Starlink project for provision of computing facilities, and PPARC for partial financial support.

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