Constraining the Birth Events of Neutron Stars

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Abstract. The prescient remark by Baade and Zwicky that supernovae beget neutron stars did little to prepare us for the remarkable variety of observational manifestations such objects display. Indeed, during the first thirty years of the empirical study of neutron stars, only a handful were found to be associated with the remnants of exploded stars. But recent X-ray and radio observations have gone a long way toward justifying the theoretical link between supernovae and neutron stars, and have revealed the wide range of properties with which newborn compact remnants are endowed. We review here our current state of knowledge regarding neutron star-supernova remnant associations, pointing out the pitfalls and the promise which such links hold. We discuss work on the ranges of neutron star velocities, initial spin periods, and magnetic field strengths, as well as on the prevalence of pulsar wind nebulae. The slots in neutron star demography held by AXPs, SGRs, radio-quiet neutron stars, and other denizens of the zoo are considered. We also present an attempt at a comprehensive census of neutron star-remnant associations and discuss the selection effects militating against finding more such relationships. We conclude that there is no pressing need to invoke large black hole or silent neutron star populations, and that the years ahead hold great promise for producing a more complete understanding of neutron star birth parameters and their subsequent evolution.

1. Introduction

The prediction by Baade & Zwicky (1934) that neutron stars would form in supernova explosions ranks among the most prophetic theoretical speculations in the history of astrophysics. An important aspect of the matter these two illustrious astronomers did not address was how such beasts could be observed. Certainly the properties of the rotation-powered pulsars discovered by Jocelyn Bell were unanticipated before 1967; the thermal X-ray emission detected from
the surfaces of a handful of nearby young pulsars over a quarter of a century later (e.g. Finley, Ögelman & Kiziloglu 1992) was the first properly predicted neutron-star observational characteristic. But the unanticipated reared its head in the interim, and the detection of soft gamma-ray bursts from the supernova remnant N49 in the Large Magellanic Cloud in 1979 (Mazets et al. 1979; Cline et al. 1982), as well as the discovery, from a source in the remnant CTB 109, of slow X-ray pulsations that could be explained neither in terms of rotation-power nor in terms of any conventional accretion mechanism (Fahlman & Gregory 1981), suggested that the words “unexpected zoo” may be applicable to the observed young neutron star population. This diversity of appearance continues to grow: X-ray point sources with properties quite different from those described above include the variable point source in RCW 103 (Tuohy & Garmire 1980; Gotthelf, Petre & Vasisht 1999; Garmire et al. 2000), the slow and X-ray variable pulsar AX J1845−0258 in G29.6+0.1 (Vasisht et al. 2000), and the point source in Cas A, made famous by the spectacular first light Chandra X-ray Observatory image (Tananbaum 1999).

It is perhaps ironic that in spite of the many possible observational manifestations of young neutron stars, one of the greatest problems in the field has been that most Galactic supernova remnants appear empty. Observational selection effects must certainly play a role, but ever-lingering is the fact that an unknown but possibly substantial fraction of massive stars undergoing core collapse might produce black holes rather than neutron stars. The size of this fraction is observationally poorly constrained. Certainly the difficulty that supernova modelers encounter in producing shock waves that can expel the outer layers of a star following the bounce in core collapse does little to dispel the concern that the black hole fraction may be large (Burrows, Hayes & Fryxell 1995; Liebendörfer et al. 2001; Janka 2001). Our ignorance of the neutron star equation of state and hence the maximum stable neutron star mass adds to this confusion (Baym & Pethick 1979). A radio pulsar is thought to be born between every 60 and 330 yr in the Galaxy (Lyne et al. 1998). This is in rough agreement with the best-estimate core-collapse Galactic supernova rate of one every $47 \pm 12$ yr (Tammann, Löffler & Schröder 1994), although a significant paucity of pulsars is suggested, and the uncertainties on both quantities are large enough to leave plenty of room for suspicion.

In this review, we discuss first the associations between SNRs and classical rotation-powered neutron stars. (Henceforth, we refer to the latter simply as “pulsars”; non-rotation-powered pulsars, in particular anomalous X-ray pulsars, will be specifically identified.) Our emphasis is less on a critique of all proposed associations (since significant reviews of this nature already exist — see e.g. Kaspi 1998, 2000; Manchester 1998) and more on what fundamental astrophysical insights such associations provide. Indeed, pulsar/supernova remnant associations have been heralded as, in principle, constraining the neutron star initial spin period, velocity and magnetic field distributions, all important for the physics of core collapse. In addition, dating pulsars is valuable in constraining the equation of state by testing cooling models (e.g. Umeda et al. 1994) — associations with supernova remnants can in principle offer independent age determinations.
We subsequently consider associations between supernova remnants and non-rotation-powered neutron stars as well as compact remnants of an uncertain nature, not merely for completeness, but as a precursor to the final section, in which we present an attempt at a synthesis of all associations. The goal here is to address the larger issue of core-collapse-remnant demographics. Similar attempts have been made in the past (e.g. Helfand & Becker 1984; Helfand 1998), although the new observational capabilities in the high energy regime represented by Chandra and XMM-Newton have led, in the last two years, to a dramatic acceleration in our identification of the compact remnants of supernova explosions. Indeed, we conclude here that current data are consistent with the notion that the majority of core-collapse events in the Galaxy do leave neutron star remnants.

2. Rotation-Powered Pulsars and Supernova Remnants

2.1. Making Associations

Associations between pulsars and remnants are generally made from the positional coincidence of an apparently young pulsar with a remnant that has no other more plausible association. Ideally, distance estimates to the two sources should agree, although neither is generally determined with high precision; similarly for rotation measures when they are available. Given the independently observed high space velocities of pulsars (Lyne & Lorimer 1994), significant offsets of the neutron star from its birth place should be expected, particularly for older associations (Gaensler & Johnston 1995). These provide a possible test of an association if a proper motion measurement can be made (although arguments for alternative causes for such offsets are presented by Gvaramadze, these proceedings).

Here we highlight several recent results concerning rotation-powered pulsar/supernova remnant associations of particular relevance to the field as a whole.

2.2. Inferring Neutron Star Space Velocities: A Dangerous Hobby

PSR B1757−24 has long been held up as the poster pulsar for high space velocities inferred from supernova remnant associations, in this case the shell remnant G5.4−1.2 (Frail & Kulkarni 1991; Manchester et al. 1991). The pulsar position, just outside the remnant boundary, suggests that the neutron star has overtaken the shell, which, unlike the pulsar, suffers deceleration from swept up interstellar material. The morphology of a small, flat-spectrum nebula protruding from G5.4−1.2, G5.27−0.90, strongly suggests ram-pressure confinement of the pulsar wind, lending significant support to this picture. Additional evidence for the pulsar having passed through the shell is the fact that the pulsar side of the remnant is brightest, and that the shell spectral index decreases monotonically along the shell with distance from the pulsar (Frail, Kassim & Weiler 1994).

The pulsar characteristic age, $\tau_c \equiv P/2\dot{P}$ (where $P$ is the spin period and $\dot{P}$ its rate of change) is 16 000 yr for PSR B1757−24. Of course, $\tau_c$ is only a good age estimator if the pulsar’s initial spin period is much shorter than that observed today, and if simple magnetic dipole braking is applicable throughout the life of
the pulsar (see Eq. 1 below). Nevertheless, using $\tau_c$ as a reasonable estimate of the true age, and assuming the pulsar was born at the shell’s geometric center, implies a pulsar proper motion of $\sim 70$ mas yr$^{-1}$, or a transverse velocity of $\sim 1800$ km s$^{-1}$ for a distance of 5 kpc. This would make PSR B1757–24 the fastest pulsar known.

However, Gaensler & Frail (2000) measured the proper motion to be $< 25$ mas yr$^{-1}$ at the 5$\sigma$ level. They interpret this result as suggesting that the system is much older than $\tau_c$ implies; they argue that the pulsar’s braking index $n$, assumed to be 3 in standard vacuum magnetic dipole braking, must be less than 1.83, and possibly even less than 1.33. Evidence exists for such low braking indices (e.g. Lyne et al. 1996; Zhang et al. 2001). Unfortunately X-ray observations of the remnant, which in principle could help independently constrain its age via the shock temperature, yield only an unconstraining upper limit, given the large absorption toward the source (see Kaspi et al., these proceedings).

Of course, the chance superposition of the pulsar and G5.4–1.2 cannot be ruled out, nor can an offset between the pulsar birth place and the shell center because of the space velocity of the progenitor (see Gvaramadze, these proceedings). In any event, the pulsar/supernova remnant picture in general is clearly complicated by the surprisingly low proper motion for PSR B1757–24. Inferring velocity estimates from possible associations appears to be a dangerous hobby.

Unaddressed by Gaensler & Frail (2000) is the interesting question of why a pulsar of apparently average velocity should exhibit so spectacular and unique a radio wind nebula. Recent Chandra observations of the system have detected X-ray emission coincident with the radio nebula, supporting the ram-pressure confined wind interpretation (see Kaspi et al., these proceedings). One possibility is that a condition for the formation of a bright ram-pressure confined pulsar wind nebula is strong rear confinement, as offered by the high pressure interior of a supernova remnant shell.

### 2.3. Neutron Star Initial Spin Periods

The age of a pulsar, $\tau$, can be calculated, assuming a constant braking index, $n$, from birth, by integrating the standard spin-down expression $\dot{\nu} \propto \nu^n$ (where $\nu \equiv 1/P$) to yield

$$\tau = \frac{P}{(n-1)P} \left[ 1 - \left( \frac{P_0}{P} \right)^n \right],$$  

where $P_0$ is the spin period at birth. Clearly, for $n = 3$ and $P_0 \ll P$, one recovers the conventional definition of characteristic age. Only the Crab pulsar has, until now, had a solid initial spin determination, $P_0 = 19$ ms, thanks to the fact that $n$ has been measured and the year of the system’s birth is known independently. Interesting constraints on other initial spin periods exist. For PSR J0537–6910, $P = 16$ ms. Given that its host remnant N157B has an approximate age of 5 kyr, this suggests $P_0 \ll 16$ ms for $n = 3$, and $P_0 < 10$ ms for $n \lesssim 2$ (Marshall et al. 1998). PSR B1951+32 in CTB 80 has $\tau_c = 107$ kyr, comparable to the dynamical shell age (Koo et al. 1990); this suggests $P_0 \ll 39$ ms for $n = 3$. Other systems provide higher and therefore less interesting upper limits on initial spin period. A variety of pulsar population synthesis models have therefore assumed
a mean value of \( P_0 \simeq 20 \text{ ms} \) in their simulations (e.g. Narayan & Ostriker 1990; Lorimer et al. 1993; Cheng & Zhang 1998; McLaughlin & Cordes 2000).

G11.2−0.3 is a bright, highly symmetrical circular shell supernova remnant detected both at radio and X-ray wavelengths (Downes 1984; Morsi & Reich 1987; Green et al. 1988). Its age, inferred from its morphology and X-ray spectrum (Aoki 1995), has been estimated to be \( \sim 2000 \text{ yr} \). A possible association with a “guest star” reported by Chinese observers in 386 A.D. also suggests youth (Clark & Stephenson 1977).

However, Torii et al. (1999) reported that the 65-ms X-ray pulsar PSR J1811−1925 discovered within the remnant (Torii et al. 1997) has \( \tau_c = 24 \text{ kyr} \). Assuming an association, they reconcile the age discrepancy by arguing that either \( P_0 \simeq 65 \text{ ms} \), or that the pulsar’s braking index is an order of magnitude larger than the canonical value of 3. Chandra X-ray observations of the system pinpointed the pulsar position as lying very close to the remnant center, supporting its inferred youth (Kaspi et al. 2001b). Given that, of the five solid braking index measurements (Lyne, Pritchard & Smith 1988; Kaspi et al. 1994; Lyne et al. 1996; Camilo et al. 2000; Zhang et al. 2001), not one has been reported as greater than 3, a value of \( \sim 30 \) for PSR J1811−1925 seems hard to swallow, making \( P_0 \simeq 62 \text{ ms} \) virtually inescapable. Nevertheless, phase coherent timing observations to verify this are planned. Furthermore, it should be possible to measure directly the expansion of the remnant in order to confirm its youth. Thus, it seems likely that the G11.2−0.3 system will provide only the second solid determination of a birth spin period for a neutron star; this system offers further proof that characteristic ages should be treated with extreme caution, particularly among apparently young pulsars.

Indeed, the latter point has broader implications. Of all pulsars known having \( \tau_c < 100 \text{ kyr} \), \( \sim 25\% \) have \( P < 90 \text{ ms} \). The long birth spin period of PSR J1811−1925 thus suggests that this fraction of young pulsars could have characteristic ages that are gross overestimates of their true age. Of course, small braking indexes could offset the discrepancy.

Recently, Murray et al. (2002) have discovered PSR J0205+6449 in the Crab-like remnant 3C 58. The latter has long been thought to be associated with the historical event recorded in 1181 A.D. (Clark & Stephenson 1977). The 66-ms pulsar, however, has a characteristic age 5400 yr, far in excess of that implied by the historical identification. This led Murray et al. (2002) to suggest that, like the G11.2−0.3 system, the initial spin period of PSR J0205+6449 would have to be long (roughly 60 ms for braking indices in the range 1.5–3). However Bietenholz, Kassim & Weiler (2001) have suggested, on the basis of remnant expansion measurements, that the true remnant age is \( \sim 5000 \text{ yr} \), in agreement with the pulsar characteristic age, calling into question the hypothesized long initial spin period.

Spruit & Phinney (1998) have suggested that there could be a correlation between initial spin period and space velocity if the supernova asymmetry that imparts a “kick” to the neutron star does so in a single blow with an impulse that is not aligned with the neutron star center-of-mass. The G11.2−0.3 pulsar has a lower transverse velocity \( (v_t < 110 \text{ km s}^{-1}) \) than those of the Crab pulsar \( (v_t = 150 \text{ km s}^{-1}; \text{Caraveo & Mignani 1999}) \), PSR B1951+32 \( (v_t \simeq 300 \text{ km s}^{-1}; \text{Fruchter et al. 1988}) \) and the N157B pulsar \( (v_t \sim 600 \text{ km s}^{-1}; \text{Bietenholz, Kassim & Weiler 2001}) \).
Wang & Gotthelf 1998). All three certainly have shorter initial spin periods, however, arguing against a single, off-center impulse scenario. A proper motion for PSR J0205+6449 has yet to be measured, but is clearly of interest.

2.4. The Observability of Plerions and the Empty Shell Problem

PSR J1119−6127 is a young radio pulsar found in the Parkes multibeam survey (Camilo et al. 2000; see contributions by Manchester et al. and Crawford et al., these proceedings). The pulsar’s period $P = 408$ ms and its rate of slowdown imply $\tau_c = 1700$ yr, a spin-down luminosity $\dot{E} = 2.3 \times 10^{36}$ erg s$^{-1}$, and, most notably, a very large implied surface dipolar magnetic field, $B = 4.1 \times 10^{13}$ G. The young age of the system is assured, as Camilo et al. (2000) have also measured the braking index $n = 2.91 \pm 0.05$.

Deep Australia Telescope Compact Array radio observations revealed a shell of emission with a non-thermal spectrum, centered on the pulsar position (Crawford et al. 2001). They name this supernova remnant shell G292.2−0.5, and note that its size supports the youth of the system. X-ray observations also detect the remnant, and are suggestive of an unusually hard X-ray spectrum (Pivovaroff et al. 2001).

Although there is tentative evidence for possible unpulsed X-ray emission associated with the pulsar, likely a synchrotron nebula, there is a noteworthy absence of any radio nebula. This makes the PSR J1119−6127 / G292.2−0.5 system an essentially unique example of an energetic, very young pulsar in a pure radio shell remnant. (PSR 0538+2817 in S147 [see Table 1] has estimated age 620 kyr and $\dot{E} = 5 \times 10^{34}$ erg s$^{-1}$, so is not expected to have an observable synchrotron nebula.) Crawford et al. (2001) show, using a detailed model of synchrotron nebular evolution (Reynolds & Chevalier 1984), that the absence of an observed radio nebula could result from strong losses suffered by the source early in its evolution, as a consequence of its high magnetic field. This system thus suggests that many empty shell supernova remnants may harbor rotation-powered pulsars that produce no observable plerions, a notion that could ameliorate the “empty shell” problem.

However, the young PSR J1846−0258, recently discovered in the supernova remnant Kes 75 also has a very high magnetic field, $4.8 \times 10^{13}$ G (Gotthelf et al. 2000), yet appears to power a radio synchrotron nebula whose flux is significantly underpredicted by the same line of reasoning used for PSR J1119−6127 (Crawford et al. 2001). A braking index for PSR J1846−0258 has yet to be measured however, so its true age is not known. If the Reynolds & Chevalier (1984) model can describe this system as well, then the pulsar should be significantly younger than PSR J1119−6127, in agreement with the claim of Gotthelf et al. (2000) that it is the youngest Galactic pulsar. Accordingly, $n \approx 3$ is expected. On the other hand, as discussed in § 2.2, low braking indexes could be common. For example, for $n = 1.8$, PSR J1846−0258 would have age $\sim 1800$ yr, larger than that of PSR J1119−6127, and hence in disagreement with the predictions of Reynolds & Chevalier (1984).

3. Alternative Neutron Star Manifestations
3.1. Anomalous X-ray Pulsars and Soft Gamma Repeaters

Anomalous X-ray Pulsars (AXPs) are a small class of pulsating X-ray sources which cannot be powered by rotation and which are highly unlikely to be powered by accretion. There are five confirmed members of this class, as well as one AXP candidate. For substantial discussions on AXPs, see the contribution by Gavriil & Kaspi in these proceedings, as well as a review by Israel, Mereghetti & Stella (2002). The Soft Gamma Repeaters (SGRs), of which there are four confirmed examples and a possible fifth, are sources which occasionally emit bursts of soft gamma-rays with an enormous fluence. They also show AXP-like pulsations in quiescence. Discussions of these sources have been presented by Hurley (2000).

Here we consider the AXPs and SGRs together because they bear a number of striking similarities that strongly suggest they are closely related (Thompson & Duncan 1996). In particular, both exhibit pulsations in the narrow range of periods from 5 s to 12 s, and both show long-term, rapid spin-down, with spin-down rates that imply characteristic ages and ultra-high magnetic fields (assuming simple dipole braking, which may not be the case). In addition, they share similar X-ray spectra in quiescence, and have similar timing properties (Woods et al. 2000; Kaplan et al. 2001; Kaspi et al. 2001a).

The magnetar model, proposed for both types of objects, posits that the X-ray emission is powered by magnetic field decay, and that the soft gamma-ray bursts come from surface cracking and subsequent particle emission arising from magnetic stresses in the neutron star crust (Thompson & Duncan 1996). A competing model for the nature of AXPs invokes accretion from a supernova fall-back disk (Chatterjee, Hernquist & Narayan 1999). However, the faintness of optical/IR counterparts (Hulleman et al. 2000, 2001) and the recently announced detection of optical pulsations from one AXP (Kern & Martin 2001) are claimed to rule out this scenario conclusively, although details are yet to emerge.

Among the primary motivations for the magnetar model was the coincidence of the first discovered SGR, SGR 0526−66, with the LMC supernova remnant N49 (Cline et al. 1982). Subsequent observations found the burster to be significantly offset from the remnant center, though still well within its projected boundary (Rothschild, Kulkarni & Lingenfelter 1994; Marsden et al. 1996). Attempts have been made to associate the three other well-localized SGRs with supernova remnants (Kulkarni et al. 1994; Hurley et al. 1999; Woods et al. 1999) but none has withstood the test of time convincingly (see Gaensler et al. 2001 for a review). This does not rule out SGRs being young neutron stars — of the ten known rotation-powered pulsars with characteristic ages under 10 kyr, two are coincident with no obvious supernova remnant. Finding associated remnants for SGRs is further complicated by their location in complicated regions of the Galactic plane associated with massive star formation (Vrba et al. 2000).

Two of the five confirmed AXPs, plus the AXP candidate, are located very near the centers of well established supernova remnants: 1E 2259+586 in CTB 109 (Fahlman & Gregory 1981), 1E 1841−045 in Kes 73 (Vasisht & Gotthelf 1997), and the possible AXP AX J1845−0258 in G29.6+0.1 (Gaensler, Gotthelf & Vasisht 1999). Although the age of 1E 2259+586 is much larger than that of CTB 109 (225 kyr versus ~ 20 kyr), this could be due to torques from Alfvén wave and particle emission (Thompson & Blaes 1998), or because the magnetic field decays on a timescale of ~ 10^4 yr (Colpi, Geppert & Page...
Kaspi & Helfand (2000). In addition, possible spin-up events have been reported (e.g. Baykal & Swank 1996) suggesting that simple age estimates are unreliable. However, recent phase-coherent observations have detected only steady spin-down for this source over 4.5 yr (Gavriil & Kaspi 2002).

Marsden et al. (2001) have claimed, on the basis of putative associations with SNRs, that the regions in which AXPs and SGRs are embedded have higher than average ambient densities, allowing for interesting mass-infall rates, and hence accretion power. In our view, this claim has been effectively rebutted by Gaensler et al. (2001); in light of the other arguments against accretion, we regard this power source as unlikely. On the other hand, Gaensler et al. (2001) argue, on the basis of associations (and the lack thereof) with supernova remnants, that SGRs are a high-velocity population, and that, in spite of the many similarities described above, likely represent a different class of sources from the AXPs. However interesting such speculation may be, we consider the conclusion premature given that (i) some AXPs (and young pulsars) are unassociated with remnants, (ii) it may be harder to find associated remnants for SGRs because of their complex environments, (iii) the numbers of both source types are small, and (iv) there are evident risks inherent in a posteriori probability estimates.

3.2. “Radio-Quiet” Neutron Stars

The epithet “radio-quiet” has been applied to a number of neutron stars and neutron-star candidates in the last few years (see Brazier & Johnston 1999 for a recent review). We begin by making clear the term’s anthropocentric definition: objects from which we astronomers, on Earth, have yet to detect radiation in the wavelength range 1 m to 10 cm. A variety of reasons can be put forth to explain this failure: (1) the pulsar’s radio radiation is beamed (an uncontroversial assumption) and our line of sight does not intercept the beam; (2) the pulsar fails to emit any low frequency radiation because the radio emission mechanism is (a) shorted out by accretion, (b) inoperative because the magnetic field is too high (Baring & Harding 2001), (c) inoperative because the polar cap potential drop is too low (Chen & Ruderman 1993; Hibschman & Arons 2001), or (d) inoperative for reasons we don’t understand; (3) the radio emission is below current search thresholds; or, (4) the X-ray point source in question is not a neutron star. Each of the sources in this category discussed below can be explained by at least one of the above possibilities.

Geminga (PSR J0631+1746) is the first, and perhaps most famous case of a radio-quiet pulsar. The second brightest object in the 100-MeV sky, the source was finally identified as a rotation-powered pulsar when X-ray pulses were detected by ROSAT (Halpern & Holt 1992). The source’s \( P, \dot{P} \), ratio of gamma-ray luminosity to spin down energy loss rate, space velocity, and other properties are typical of intermediate-age (\( \sim 10^{5.5} \) yr) radio pulsars. Its proximity and radio flux density upper limit place its observable radio luminosity (from the 320 MHz flux density) a factor of ten below that of the least luminous pulsar known, and a factor of \( \sim 300 \) below the weakest pulsars of comparable age and \( E \) (McLaughlin et al. 1999). While other physical mechanisms may be responsible for the absence of radio emission (e.g. quenching of the low-altitude radio particle accelerator by pairs streaming back toward the surface
from the outer-gap gamma-ray emission region; Halpern & Ruderman 1993), simple beaming remains a viable explanation.

The X-ray point source near the center of the southern supernova remnant PKS 1209–51/52 (G296.5+10.0) has also been known for more than twenty years (Helfand and Becker 1984), and reasonably stringent radio upper limits have been obtained for any pulsed flux from the source (Kaspi et al. 1996). Recently, Zavlin et al. (2000) have detected X-ray pulsations with a period of 0.424 s. While a period derivative has yet to be determined, the X-ray properties of the source mark it as—dare we say it—“prototypical of an emerging class” of X-ray sources in supernova remnants. It has an X-ray luminosity of $\sim 10^{35.5} \text{ erg s}^{-1}$ and a soft X-ray spectrum which, if parameterized as a black body, yields a temperature of 0.25 keV. The original notion that sources such as this were cooling neutron stars has been challenged by the fact that the inferred emitting radius is only $1.1 \text{ km}$. However, when complex neutron star atmospheres are used to fit the spectrum (and lower the inferred temperature), the emitting radius can be raised to a plausible value (Zavlin, Pavlov, and Trümper 1998). There is, as yet, no complete model that both incorporates observed small pulsed fraction ($\sim 8\%$) and the spectral fits (Pavlov, this volume). The radio upper limit translates to a luminosity significantly below that of most other young sources, but a few objects with comparable periods have lower radio luminosities. The lack of a radio synchrotron nebula suggests a comparison with PSR J1119–6127 (§2.4) which has a similar period, age, and surrounding shell-type supernova remnant. If a high value of $\dot{P}$ is measured for this source, the analogy will be all the more compelling.

Three other point-like X-ray sources inside SNR shells have very similar X-ray properties to the PKS 1209–51/52 central source and, in common with this source and Geminga, all lack evidence for surrounding pulsar wind nebulae. These objects lie within the confines of RCW 103 (Tuohy & Garmire 1980), Puppis A (Petre, Becker, & Winkler 1996), and Cas A (Tananbaum 1999), the youngest known remnant in the Galaxy. All have X-ray temperatures of 0.3–0.6 keV and estimated X-ray luminosities within a factor of three of $10^{33.5} \text{ erg s}^{-1}$, although the first of these has been reported to have varied by more than a factor of ten on a timescale of months (Gotthelf, Petre & Vasisht 1999; Garmire et al. 2000). In addition, the inferred blackbody radii for each source are 0.5 to 2 km (see Chakrabarty at al. 2001 for a detailed comparison of the X-ray properties of these objects with those of other young neutron star classes). While it is possible to envision scenarios in which a small hotspot rather than the whole neutron star is producing most of the X-ray emission (e.g. as a consequence of chemical abundance gradients in the stellar envelope [Pavlov et al. 2000] or as a result of accretion onto the poles of a weakly magnetized star [Chakrabarty et al. 2001]), such localized emission must, perforce, suffer rotational modulation, a phenomenon yet to be observed in these three objects, although deeper searches for pulsations continue.

A note of caution on the radio upper limits for these objects is occasioned by the recent result from Camilo et al. (2002) announcing the discovery of a radio pulsar in G292.0+1.8. They show that this young ($< 2000 \text{ yr}$) pulsar has a radio luminosity of only $\sim 2 \text{ mJy kpc}^2$, more than an order of magnitude below the least luminous young pulsar previously known; this value is a factor
of ten below the upper limit on the Cas A X-ray point source (McLaughlin et al. 2001), and is similar to the current upper limits for the recently discovered rotation-powered pulsar in 3C 58 and the other three sources discussed here.

3.3. Binaries

The majority of all massive stars are in binaries. The preceding discussion of a score of remnants of such stars, however, has included only single systems. The canonical explanation for the fact that only two of over 1000 (unrecycled) pulsars has a binary companion is that, either through the loss of more than half the mass of the system, or as a consequence of an asymmetric kick at the time of the explosion, most binaries are unbound by a neutron star’s progenitor supernova. Population synthesis models of core-collapse explosions in binary systems can, with some tweaking, do a reasonable job of reproducing the observed population of high-mass X-ray binaries containing neutron stars as well as the single pulsar population.

The detailed population synthesis by Portegies Zwart & Verbunt (1996) provides a useful example of such a calculation. They adopt a core-collapse supernova rate of 1.6 per century and a population in which 60% of the massive stars are single and 40% are in binaries. They include the effects of primordial binary eccentricities and mass transfer. In their models with no kick provided to the neutron star at birth, they predict 1 in 8 young neutron stars should have a companion. However, this scenario overproduces the number of Be star binaries and other binary pulsar systems by a large factor. With a natal kick of 450 km s$^{-1}$, the predicted number of neutron stars with a binary companion at birth falls to 1 in 90 (and nearly 25% of these are Her X-1 type systems which, the authors acknowledge, are over-produced in all their models). This binary birthrate of roughly one system per 5000 yr means we should not expect more than half a dozen such systems in the Galaxy to be associated with their progenitor supernova remnants. In fact, we know of only two candidates for young neutron stars associated with supernova remnants which do have binary companions. Despite decades of study, however, both cases remain ambiguous.

Cir X-1 certainly contains a neutron star because it exhibits X-ray bursts (Tennant, Fabian & Shafer 1986), and is indubitably a binary with a 16.6 day period (Kaluzienski et al. 1976). However, it lies 25′ from the center of G321.9−0.3, and requires a systemic space velocity of > 580 km s$^{-1}$ to explain its location. Tauris et al. (1999) explore the implications of this association. They find a minimum age for the remnant of 60 000 yr and a required impulse to the system of 500–1000 km s$^{-1}$. While not energetically excluded, this is uncomfortably large compared to the observed velocities of most pulsars (i.e. had the neutron star alone received such a kick, its velocity would have been well in excess of 1000 km s$^{-1}$). Thus, despite some morphological evidence for the association (Stewart et al. 1993; Fender et al. 1998), we regard the connection of the binary system with the supernova remnant as less than certain.

SS 433 is the other candidate system. In this case the binary nature of the source is also unambiguous, but opinion is divided as to whether W50 is a supernova remnant (Kirshner & Chevalier 1980) or a wind-blown bubble produced by the source’s relativistic jets (Königl 1983), and whether the compact object is a neutron star or a black hole. On the latter subject, opinion is divided, some-
times within the minds of individual authors (cf. Zwitter & Calvani 1989 and D’Odorico et al. 1991). Long considered unique in the Galaxy for its precessing relativistic jets, the recent discovery of the “micro-quasars” which show similar radio jets (Mirabel & Rodríguez 1999) is relevant; Safi-Harb, Durouchoux & Petre (2001) have placed SS 433 in this class which is apparently dominated by black hole accretors.

Even if one accepts both sources as examples of young binary neutron stars associated with supernova remnants, they represent less than 5% of the confirmed young neutron stars discussed above and in §4. As noted earlier, this is to be expected if neutron stars receive a substantial impulse at birth. As the observed population of pulsars in supernova remnants becomes more complete and more fully characterized, it will be able to provide a constraint on the range of kicks required to unbind most systems at the time of the first supernova event. A corollary of this high binary destruction rate is that many remnants should contain within their shells the discarded binary companions. Finding such objects and determining their space velocities would further constrain the kinematic consequences of pulsar birth.

4. A Status Report on Associations

4.1. The Census

Recognizing the variety of manifestations young neutron stars can exhibit and the ambiguities (cited above) involved in making definitive associations, we nonetheless attempt here a summary of our current state of knowledge. In Table 1, we provide a list of all remnants which at least two workers in the field (the authors) can agree exhibit some sign of an associated young neutron star. We utilize the standard SNR classifications of shell-like, composite and Crab-like. We divide the table into four categories representing various levels of certainty concerning the evidence: the detection of a young, rotation-powered pulsar within the confines of the remnant, the detection of an X-ray point source, the detection of a diffuse, non-thermal X-ray nebula indicating current particle acceleration accompanied by a radio synchrotron nebula, and the detection of a radio synchrotron nebula alone lacking high energy confirmation.

Seventeen years after the discovery of the first radio pulsar, only three rotation-powered neutron stars where known to be associated with Galactic supernova remnants (Helfand & Becker 1984). Seventeen years after that review, the number has grown to fifteen, with nearly half of these discovered in the past few years. Two additional examples are found in the Large Magellanic Cloud. In all but two cases, the neutron star is surrounded by a radio and/or X-ray pulsar wind nebula. Thus, in at least \( \sim 10\% \) of the cataloged remnants in the Galaxy likely to have resulted from a core-collapse supernova\(^1\) (and a considerably larger fraction of the younger remnants — see below), we directly observe the “canonical” result: a rapidly spinning, magnetized neutron star losing energy via a relativistic wind which powers a surrounding nebula.

\(^1\)As argued below, \( \sim 50 \) cataloged Galactic remnants had SN Ia progenitors.
Quantitatively, however, this population does not follow the canon which posits the Crab pulsar as a prototype. We have known this implicitly for three decades: there should be at least half a dozen pulsars in the Galaxy within a factor of two of the Crab in age if we adopt the Lyne et al. (1998) lower birthrate limit of 1 per 330 yr, and more than a dozen for the best birthrate estimate. Yet the first X-ray surveys of the sky showed no such objects of comparable luminosity. Thus, the $\sim 19$ ms initial spin period, $\sim 10^{12.5}$ G field, relatively low velocity ($\sim 150$ km s$^{-1}$), and confining filaments are at least not all typical. Indeed, the observed periods for the young neutron stars known today range over one and a half orders of magnitude: from 16 ms for the source in N157B to 424 ms for the X-ray pulsar in PKS 1209–51/52; even inferred spin periods at birth have at least a spread of a factor of ten (§2.3). Magnetic field strengths are likewise broadly distributed, from $1 \times 10^{12}$ G for N157B to $50 \times 10^{12}$ G for the pulsar in Kes 75. While the relationship among these observed parameters and the initial periods and magnetic field strengths is not at all well understood, it is likely that a considerable range in birth properties exists, and that the Crab represents an unusual combination that renders it far more conspicuous than most young neutron stars.

The second set of candidate young neutron stars contains the varied collection of X-ray point sources associated with supernova remnants (or putative remnants) discussed in §3. Two are AXPs, one is a soft gamma-ray repeater, and at least two are X-ray binaries (SS 433 — not obviously a neutron star — and Cir X-1). The remainder are X-ray point sources of an ambiguous nature, although those with known, pulsar-like periods (PKS 1209–51/52) or with surrounding X-ray and radio synchrotron nebulae (e.g. G54.1+0.3, G0.9+0.1) are highly likely to be confirmed as neutron stars in the near future.

Given the short ($\sim 1$ to 100 yr) lifetime of X-ray-emitting synchrotron electrons in the expected nebular magnetic fields ($\sim 10^{-4}$ G), a centrally peaked diffuse X-ray source with a power-law X-ray spectrum inside a supernova remnant provides a compelling argument for the presence of a young pulsar even when no X-ray or radio point source is detected. Nine additional remnants exhibit such evidence. Deeper imaging observations with Chandra, and timing observations with XMM-Newton and radio telescopes may soon reveal pulsars within them, just as recent observations of 3C 58 (Murray et al. 2002), G106.6+2.9 (Halpern et al. 2001), and G292.0+1.8 (Camilo et al. 2002) have promoted these objects to the confirmed category. Less certain candidates are found among the eight objects which appear to have a flat-spectrum synchrotron component in their radio spectra. For many of these, the X-ray upper limits are weak or non-existent; future observations could readily confirm or refute the presence of an active young pulsar. Nonetheless, the final total for cataloged remnants with some reasonably sound evidence for a contemporaneous young neutron star is 48 (plus three in the LMC) — a substantial improvement over the handful known only a decade ago.

4.2. Selection Effects

The rapid rise in the last few years in the number of compact-object/SNR associations demonstrates that previous searches were simply lacking the sensitivity necessary to detect the various manifestations of young neutron stars. Yet an
examination of the properties of the remnants in Table 1 shows clearly that our current sample remains substantially incomplete. In Table 2, we display the Galactic longitude- and latitude-dependence, as well as the angular size distribution, for the remnants exhibiting evidence for a compact object. The results demonstrate that striking selection effects remain in the sample. For example, only 10% (7/69) of the remnants within 20° of the Galactic Center show such evidence, whereas the fraction in the sector 180° < l < 300° is 33%. Higher X-ray absorbing column densities, smaller angular diameters and greater distances are no doubt principal culprits militating against finding PWNe in remnants toward the inner Galaxy, as are dispersion smearing, multipath scattering, and the high surface brightness of the radio emission from the Galactic plane when conducting radio pulsar searches. The same factors bias the latitude distribution of the detected fraction: 13% for |b| < 0.3° versus 31% for 0.3° < |b| < 1.0°. The fraction at higher latitudes drops to 24%, but this may in part be due to the larger fraction of SN Ia's found farther from the plane of the Galaxy.

The angular size dependence shows a possible age effect: 35% of remnants with a diameter \( D < 5' \) host a neutron star, whereas for remnants in the range 10' < D < 20' the fraction falls to 13%. The fraction rises again to 25–30% for very large diameter remnants, most likely because these are nearby objects in which very faint pulsars and/or synchrotron nebulae can be detected.

In the most recent SNR catalog (Green 2000), 225 remnants are listed; a handful of additions have been suggested at this meeting. According to the best estimates of Galactic SN rates (van den Bergh & Tammann 1991), roughly 15% of all explosions are expected to be of Type Ia (and thus, in most, but not all scenarios, are not expected to leave a compact remnant). We can expect Type Ia remnants to be overrepresented in the current sample owing to their larger scale height; it is easier to detect remnants away from the tangle of radio-emitting H II regions and diffuse non-thermal emission in the Galactic plane. Thus, we estimate that at least 40–50 remnants in the current compilation result from Type Ia explosions. In addition, it must be the case that some fraction of core-collapse explosions produce black holes, since we have extremely strong evidence for the existence of stellar-mass black holes in more than a dozen binary systems. We use ten as a conservative placeholder for the number of currently catalogued remnants which produced black holes. This leaves \( \sim 170 \) remnants in which we should expect to find a neutron star remnant. Table 1 shows that we already have such evidence in 48 cases or nearly one-third of the total, while Table 2 offers evidence that our current surveys are incomplete by at least a factor of two.

Thus, contrary to the situation just three years ago (Helfand 1998), we argue that there is no need to invoke either a large black hole production rate or the creation of invisible neutron stars in order to explain the statistics of neutron star supernova remnant associations.

5. Conclusions

As with any maturing astronomical field (or in life, for that matter), the simple pictures of youth grow with time more complicated and more frustrating — or richer, depending on one's personal gestalt. The triumphalist picture of science
as proceeding from an inspired insight (Baade and Zwicky 1934) to a more
detailed model (Pacini 1967) to an experimental confirmation (Hewish et al.
1968) has always been a trifle simplistic. Supernovae do not always “represent
the transition from an ordinary star into a neutron star”, and the ones that do
evidently provide us with a host of possible manifestations. We have presented
here a snapshot of our current state of knowledge concerning the genesis of
neutron stars. The fact the we cite no fewer than 39 references from within the
past twenty-four months suggests the subject is a vibrant one which is benefiting
from significant improvements in observational sensitivity, primarily in the X-ray
and radio bands. It took thirty years to find the first ten secure pulsar-remnant
associations and less than three years to find the next five. The large number of
candidates discussed above assures continuing rapid progress. The longstanding
embarrassment of all those empty supernova remnants appears to be significantly
ameliorated and is replaced by the challenge of overcoming the selection effects
which hamper discoveries, and understanding the many ways in which young
neutron stars manifest their presence. Such understanding might even lead to
quantitative constraints on the conditions present in core-collapse explosions and
the resulting nucleosynthetic yields which determine the chemical composition
of the Galaxy.

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Table 1. The current neutron star/supernova remnant census

| Evidence                  | Plerionic Remnant                                                                 | Composite Remnant                                                                 | Pure Shell Remnant                                                                 |
|---------------------------|------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| **Pulsar + Supernova Remnant (15+2)** | G106.6±2.9 [PSR J0229+6114] <br>G130.7±3.1 (3C 58) [PSR J0205+64] <br>G184.6±5.8 (Crab) [PSR B0531+21] <br>N157B (in LMC) [PSR J0537−6917] | G5.4−1.2 (Duck) [PSR B1757−24] <br>G11.2−0.3 [PSR J1811−1925] <br>G29.7−0.3 (Kes 75) [PSR J1846−0258] <br>G34.7−0.4 (W44) [PSR B1853+01] <br>G69.0±2.7 (CTB 80) [PSR B1951+32] | G180.0−1.7 (S147) [PSR J0538+2817] <br>G292.2−0.5 [PSR J1119−6127] |
| **Exotic/Possible NS + Supernova Remnant (16+1)** | G54.1±0.3 [CXOU J193030.1+185214] | G0.9±0.1 [SAX J1747−2809] <br>G119.5±10.2 (CTA 1) [RX J000702+7302.9] <br>G189.1±30.0 (IC 443) [CXOU J061705.3+22127] <br>G291.0−0.1 (MSH 11−63) [AX J1111−6040] | G27.4±0.0 (Kes 73) [AX J1845−0258] (AXP) <br>G29.6±0.1 [AX J1845−0258] (AXP?) <br>G39.7−2.0 [SS 433] (binary) <br>G78.2±2.1 (gamma Cygni) [RX J2020.2+4026] (NS?) <br>G119.1−1.0 (CTB 109) [1E 2259+586] (AXP) <br>G111.7−2.1 (Cau A) [CXO J232327.9+584842] (NS?) <br>G299.4−3.4 (Puppis A) [RX J0822−4300] (NS?) <br>G266.2−2.1 (RX J0852.0−4622) [SAX J0852.0−4615] (NS?) <br>G296.5+10.0 (PKS 1209−51/52) [1E 1207.4−5209] <br>G321.9−0.3 (Cr X-1) (binary) <br>G332.4−0.4 [RCW 103] (1E 161348−5055) (NS?)<br>N49 (in LMC) [SGR 0526−66] (SGR) |
| **X-ray and Radio nebula (9)** | G20.0−0.2 <br>G21.5±0.9 <br>G74.9±1.2 <br>G328.4±0.2 | G16.7±0.1 <br>G39.2−0.3 <br>G126.3−1.8 (MSH 15−56) | G327.1−1.1 <br>G344.7−0.1 |
| **Radio nebula only (8)** | G6.1±1.2 <br>G27.8±0.6 <br>G63.7±1.1 | G24.7±0.6 <br>G293.8±0.6 <br>G318.9±0.4 | G322.5−0.1 <br>G351.2±0.1 |
Table 2. The distributions of SNRs containing evidence of a young neutron star

| Galactic Longitude | $-20^\circ < l < 20^\circ$ | $20^\circ < l < 60^\circ$ | $60^\circ < l < 180^\circ$ | $180^\circ < l < 300^\circ$ | $300^\circ < l < 340^\circ$ |
|--------------------|-----------------------------|----------------------------|--------------------------|-----------------------------|-----------------------------|
|                    | 7/69                        | 11/43                      | 11/39                    | 10/30                       | 9/45                        |

| Galactic Latitude  | $|b| < 0.3^\circ$ | $0.3^\circ < |b| < 1.0^\circ$ | $|b| > 1.0^\circ$ |
|--------------------|-----------------|----------------------------|-------------------|
|                    | 11/85           | 15/49                      | 22/92             |

| Angular Size       | $< 5'$ | $5' - 10'$ | $10' - 20'$ | $20' - 40'$ | $40' - 80'$ | $80' - 160'$ | $> 160'$ |
|--------------------|--------|------------|------------|------------|------------|-------------|---------|
|                    | 7/20   | 12/40      | 7/53       | 10/60      | 6/33       | 4/14        | 2/6     |