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NATURE VERSUS NURTURE: THE ORIGIN OF SOFT GAMMA-RAY REPEATERS AND ANOMALOUS X-RAY PULSARS

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ABSTRACT

Soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are young and radio-quiet X-ray pulsars that have been rapidly spun-down to slow spin periods clustered in the range 5–12 s. Most of these unusual pulsars also appear to be associated with supernova shell remnants (SNRs) with typical ages less than 30 kyr. By examining the sizes of these remnants versus their ages, we demonstrate that the interstellar media that surrounded the SGR and AXP progenitors and their SNRs were unusually dense compared to the environments around most young radio pulsars and SNRs. We explore the implications of this evidence on magnetar and propeller-based models for the rapid spin-down of SGRs and AXPs. We find that evidence of dense environments is not consistent with the magnetar model unless a causal link can be shown between the development of magnetars and the external interstellar medium. Propeller-driven spin-down by fossil accretion disks for SGRs and AXPs appears to be consistent with dense environments since the environment can facilitate the formation of such a disk. This may occur in two ways: (1) formation of a "pushback" disk from the innermost ejecta pushed back by prompt reverse shocks from supernova remnant interactions with massive progenitor wind material stalled in dense surrounding gas or (2) acquisition of disks by a high-velocity neutron stars, which may be able to capture sufficient amounts of comoving outflowing ejecta slowed by the prompt reverse shocks in dense environments.

Subject headings: gamma rays: observations — pulsars: general — stars: neutron — supernova remnants — X-rays: stars

1. INTRODUCTION

Soft gamma-ray repeaters (SGRs) are neutron stars whose multiple bursts of gamma-rays distinguish them from other gamma-ray burst sources (e.g., Hurley 2000 for a recent review). SGRs are also unusual X-ray pulsars in that they have spin periods clustered in the interval 5–8 s and they all appear to be associated (Cline et al. 1982; Felten 1981; Kulkarni & Frail 1993; Vasisht et al. 1994; Hurley et al. 1999a, 1999c; Corbel et al. 1999; Cline et al. 2000) with supernova remnants (SNRs), which limits their average age to approximately 20 kyr (Braun, Goss, & Lyne 1989). The angular offsets of the SGRs from the apparent centers of their associated supernova remnant shells indicate that SGRs are endowed with space velocities greater than 500 km s^{-1}, which are greater than the space velocities of most radio pulsars (Cordes & Chernoff 1998). Anomalous X-ray pulsars (AXPs) are similar to SGRs in that they are radio-quiet X-ray pulsars with spin periods clustered in the range 6–12 s and have persistent X-ray luminosities similar to those of SGRs ($\sim 10^{35}$ ergs s^{-1}; see e.g., Stella, Israel, & Mereghetti 1998 for a recent review). Most AXPs appear to be associated with supernova remnants, and therefore, like the SGRs, they are also thought to be young neutron stars. The spin periods of both AXPs and SGRs increase with time (spinning-down) and show no evidence for intervals of decreasing spin period (spin-up), although the spin-down rates of many of the SGRs and AXPs appear to be variable or "bumpy" (e.g., Baykal & Swank 1996; Marsden, Rothschild, & Lingenfelter 1999; Woods et al. 1999c, 2000; for a different viewpoint see Kaspi, Chakrabarty, & Steinberger 1999).

The lack of identified companions at non–X-ray wavelengths (e.g., Stella et al. 1998) and Doppler shifts associated with binary orbital motion (Mereghetti, Israel, & Stella 1998), together with the problem of accelerating binaries to space velocities greater than 1000 km s^{-1} (Rothschild, Kulkarni, & Lingenfelter 1994), implies that SGRs and AXPs are not members of high-mass binary systems, although low-mass systems with stellar companions of less than 1 $M_\odot$ are not constrained in most cases. If SGRs and AXPs spin-down primarily via the emission of magnetic dipole radiation (MDR), as do radio pulsars, then they must have surface dipole fields of $\sim 10^{14}$ G or greater (i.e., they must be "magnetars"; e.g., Thompson & Duncan 1995). Observations of SGR 1806−20 (Kouveliotou et al. 1998) and SGR 1900+14 (Marsden et al. 1999; Woods et al. 1999c), however, indicate that the present-day spin-down rates of these SGRs are inconsistent with simple MDR, given the ages of their associated supernova remnants (Harding, Contopoulos, & Kazanas 1999; Rothschild, Marsden, & Lingenfelter 1999), and imply that the spin-downs are due to winds. Magnetar-strength fields might still be possible in these sources, however, if Alfvén wave

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wind emission is infrequent and intermittent (Harding et al. 1999), so that the presently observed spin-down rates are atypical. Alternative scenarios for SGRs and AXPs involving typical pulsar magnetic fields ($\sim 10^{12}$ G) have been proposed (van Paradijs et al. 1995; Alpar 2000; Chatterjee, Hernquist, & Narayan 2000; Chatterjee & Hernquist 2000). In these models, the SGRs and AXPs have spun-down rapidly via magnetospheric accretion torques from outflowing "propeller effect" winds. The assumed sources of the magnetospheric material are either fallback accretion disks (Alpar 2000; Chatterjee et al. 2000; Chatterjee & Hernquist 2000), or fossil disks formed from expanding supernova ejecta intercepted by high-velocity neutron stars (van Paradijs et al. 1995; Corbet et al. 1995).

Here we present a fresh look at evidence that suggests that SGRs and AXPs are born into unusually dense environments. We show that the environments of the SGR and AXP progenitors into which their SNRs expand are the dense, warm, and cool phases of the interstellar medium (ISM) and not the hot tenuous phase of the ISM where most of the neutron-star–producing, core-collapse supernovae of massive O and B stars occur and where most young radio pulsars are found. This implies that there is an environmental factor influencing the development of SGRs and AXPs. The structure of this paper is as follows. We first discuss the typical environments of supernova progenitors in § 2 and then supernova remnants associated with SGRs and AXPs in § 3, followed by a discussion of the SGR and AXP ages and distances are in § 4. In § 5 the density of the SGR and AXP progenitor environments is discussed, and in § 6 a similar analysis is done for the SNRs associated with young radio pulsars. In § 7 we discuss the statistical significance of the results and the implications for magnetar and propeller-based models for SGRs and AXPs. Finally, the Appendix contains a short discussion of the ages, distances, and other information for each SGR and AXP.

2. THE ENVIRONMENTS OF SUPERNOVA PROGENITORS

What are the environments typical of neutron star progenitors? Observations clearly show that the majority of neutron stars are formed in "superbubbles": evacuated regions of the ISM that surround the OB associations in which the massive progenitors of most neutron stars live. This is because most O and B stars (>80%) are observed (e.g., McCray & Snow 1979) to occur in clusters formed from giant molecular clouds ($>10^5\ M_\odot$); much smaller clouds are disrupted by the radiation and winds from the first O star that forms. These massive ($>8\ M_\odot$; Woosley & Weaver 1995) and slow-moving (~ 4 km s^{-1}; Blaauw 1961) O and B star progenitors of Type II and Ib/c supernovae do not travel far from their birthplaces during their relatively short (<30 Myr; Schaller et al. 1992) lives. The supernovae from these massive stars are therefore heavily clustered in space and time and form vast (>100 pc) H II regions/superbubbles (e.g., Mac Low & McCray 1988) filled with a hot ($>10^6$ K) and tenuous ($n \sim 10^{-3}$ cm^{-3}) gas.

There is also direct observational evidence that the great majority (>80%) of neutron star stars are born into superbubbles consisting of hot and diffuse ISM gas. Observations of a sample of 49 spectroscopically identified Type II and Ib/c core-collapse supernovae occurring in face-on late-type spiral galaxies by van Dyk, Hamuy, & Filippenko (1996) found that 72% ± 10% of Type II and 68% ± 12% of Type Ib/c supernovae are in resolvable giant H II region superbubbles. We suggest that these fractions are, in fact, only a lower limit on the occurrence of core-collapse supernovae in superbubbles, because of the difficulty in detecting faint H II regions in distant galaxies. Correcting for this effect using the Hα luminosity distributions of Kennicutt, Edgar, & Hodge (1989), we find that the Hα threshold used by van Dyk et al. (1996) would have allowed them to resolve only 76% of the H II regions in their sample galaxies. This clearly suggests that the great majority—i.e., 90% ± 10%—of neutron star progenitors reside in the hot and diffuse ($n < 0.01$ cm^{-3}) ISM in superbubbles, with less than 20% occurring in the denser phases of the ISM.

When one corrects for selection effects, the distribution of surface brightness of all detected Galactic supernova remnants provides another measure of the fractions of supernovae occurring in the warm and hot phases of the ISM. Detections of radio remnants are limited by surface brightness, which is independent of their distance, and SNRs in the denser ISM have larger surface brightnesses than SNRs of the same age in the hot/diffuse ISM (e.g., Gull 1973). A study (Higdon & Lingenfelter 1980) of the age versus surface brightness of the remnants of historical supernovae, using Gull's model, suggests that the maximum detectable ages of radio supernova remnants above a nominal surface brightness density of 10^{-21} W m^{-2} Hz^{-1} sr^{-1} at 408 MHz are roughly 20 kyr in the warm ($n = 0.1$ cm^{-3}) gas and 6 kyr in the hot superbubble ($n = 0.001$ cm^{-3}) gas. Combining this with an analysis of the number distribution of SNRs as a function of surface brightness suggests that about 30% of the detected radio SNRs are in the warm denser ($n > 0.1$ cm^{-3}) phase of the ISM (e.g., Higdon & Lingenfelter 1980). This implies that only about 10% of the supernovae occur in the warm ($n > 0.1$ cm^{-3}) ISM[2] and about 90% in the hot phase, since, for a total (including Type Ia) SN rate of 1 SN every 30 yr, there are then roughly 180 SNR younger than 6 kyr that are detectable in the hot superbubble ISM and roughly 70 SNR younger than 20 kyr that are detectable in the denser warm ISM, or about 30% of the detected radio SNRs in the warm ISM—as the observed distribution implies.

3. THE SUPERNOVA REMNANTS ASSOCIATED WITH SGRs AND AXPs

The environments of SGRs and AXPs are probed by the blast waves of their associated supernova remnants, and from the size of the remnant shell as a function of the age we can constrain the external density. In Table 1 we have listed the 12 known SGRs and AXPs and their associated supernova remnant shells. For more information on the individual SGRs and AXPs, see the recent reviews of Hurley (2000) and Mereghetti (1999), and the Appendix. We include the source AXP 1845−0258—although no period derivative has been measured for this source—because it is commonly cited as an AXP (see e.g., the discussion in Gaensler et al. 1999). We also include AXP 0720−3125 for completeness, although its identification as an AXP has been questioned as well (see the Appendix). The new and tentative SGR 1801−23 has also been included on the basis of two soft

[2] We should mention that Higdon & Lingenfelter (1980) further suggested that this fraction represented the filling factor of the warm ISM, on the mistaken assumption that the supernovae were uniformly distributed rather than being predominantly clumped in OB associations.

TABLE 1

THE SUPERNOVA REMNANTS OF SGRs AND AXPs

Object	Period (s)	SNR	Age[a] (kyr)	Radius[b] (pc)	θ_*/θ_{SNR}
AXP 1841−045	11.8	Kes 73	1.5 ± 1.0	3.5–4.4	0.1
SGR 0526−66	8.0	N49	10 ± 5	7.1–8.0	0.8
AXP 2259+58.6	6.98	CTB 109	10 ± 7	16–24	0.2
AXP 1845−0258......	6.97	G29.6+0.1	15 ± 14	6.5–9.8	0.1
SGR 1627−41	6.4?	G337.0−0.1	16 ± 14	2.3–2.5	2.3
SGR 1801−23	...	W28[c]	16 ± 14	7.0–17.5	0.1
AXP 1709−40	11.0	G346.6−0.2[c]	17 ± 13	4.4–7.3	1.7
SGR 1806−20	7.47	G10.0−0.3	17 ± 13	14–17	0.5
SGR 1900+14	5.16	G42.8+0.6	20 ± 10	11–31	1.4
AXP 1048−5937......	6.45	G287.8−0.5[c]	20 ± 10	9.1–10.2	2.2
AXP 0720−3125......	8.39	...[d]	40[e]	...	...
AXP 0142+615	8.69	...[f]	60[e]	...	...

[a] SNR age (see the Appendix notes).
[b] Radius of radio shell (see the Appendix and distances in Table 2).
[c] "Tentative" remnant identification (see text).
[d] Too close to identify radio remnant.
[e] MDR timing age since there is no identified SNR.
[f] In/behind molecular cloud (no identified remnant).

gamma-ray bursts consistent with a single location on the sky (Cline et al. 2000).

The identifications of the associated remnants are based on positional coincidences between the remnant and the SGR/AXP and, in some cases, on similar distances as implied by the hydrogen column densities measured from the X-ray spectrum of the SGR/AXP and its associated remnant. Based on these criteria, associated SNRs have been previously been identified for seven of the 12 SGRs and AXPs (see Table 1 and the Appendix). Using these same criteria, we suggest three additional SNR associations with SGR/AXPs (also included in Table 1 and the Appendix). We suggest two new AXP/SNR associations, AXP 1709−40 with the SNR G346.6−0.2 (see D. A. Green 2000[3]) and AXP 1048−5937 with G287.8−0.5 (Jones 1973), based on the near coincident positions between each AXP and a known supernova remnant and also (for AXP 1048−5937/G287.8−0.5) on similar implied distances for the AXP and the remnant. These two associations may have been discounted previously because they would imply larger than average neutron star velocities, but in view of the comparable velocities implied for three of the SGRs, these possible associations should be considered. AXP 1048−5937 lies 2.2 shell radii from the apparent center of SNR G287.8−0.5, which is associated with the Carina Nebula, a region of massive star formation at a distance ∼2.5−2.8 pc (Thé & Vleeming 1971; Seward & Chlebowski 1982). This relatively small distance of the SNR is quite consistent (see Fig. 2) with the low $N_H = (0.45 \pm 0.10) \times 10^{22}$ cm^{-2} found from the AXP 1048−5937 X-ray spectral fits (Oosterbroeck et al. 1998). For an estimated SNR age of ∼20 kyr, the displacement of the AXP implies a relatively modest neutron star velocity of ∼1000 km s^{-1}. A similar transverse velocity is indicated by the association of AXP 1709−40, which lies 1.7 shell radii from the center of the well-defined shell remnant G346.6−0.2, assuming a similar age and a distance of 3–5 kpc, based on Galactic structure. Such an SNR distance is quite consistent with its association with AXP 1709−40, which has an X-ray absorption $N_H = (1.81 \pm 0.07) \times 10^{22}$ cm^{-2} (Sugizaki et al. 1997). We also propose that the new SGR candidate 1801−23 (Cline et al. 2000) may be associated with the well-studied SNR W28. Although there is no distance estimate to the SGR (Cline et al. 2000), W28 is the only known SNR through which the thin SGR error box passes. Therefore we regard the tentative W28/SGR 1801−23 association as promising and encourage observations to search for X-ray point sources (e.g., Andrews et al. 1983) within the remnant, which may be the SGR counterpart. We include these three tentative SNR associations because they are suggestive, but as we show in § 7.1, these data can be left out of the sample without affecting the overall conclusions of our analysis.

Using the Catalogue of Supernova Remnants (Green 2000), we are unable to identify any possible remnants associated with AXP 0720−3125 and AXP 0142+615, which may be the two oldest AXPs based on their pulsar timing ages $0.5P/\dot{P}$, where P is the pulsar period and $\dot{P}$ is the period derivative, of 40 (Haberl et al. 1997) and 60 kyr (e.g., White et al. 1996), respectively. For AXP 0720−3125 the lack of an associated remnant is not surprising, because this source is thought to be so close (∼100 pc) that a neutron star with a velocity of ∼1000 km s^{-1} would have traveled ∼40 pc in 40 kyr and hence could have originated from a large area of the sky. In addition, the large-scale radio surveys of the Galactic plane appear to be incomplete for very large (>1°) diameter remnants (e.g., Duncan et al. 1997), indicating that such a remnant could easily go undetected. AXP 0142+615 is situated in or behind a molecular cloud complex (Israel, Mereghetti, & Stella 1994; White et al. 1996), and if its associated remnant expanded in high-density material, it may have already passed into the radiative phase and faded below the surface brightness detection threshold. Therefore the detection of the remnants associated with both AXP 0720−3125 and AXP 0142+615 would be difficult, and we cannot assign meaningful limits to the physical size of their (unknown) associated remnants,

[3] D. A. Green, 2000, A Catalogue of Galactic Supernova Remnants (2000 August version), Mullard Radio Astronomy Observatory, Cambridge, United Kingdom (available at http://www.mrao.cam.ac.uk/surveys/snrs).

given the present data. We encourage new deep observations of the regions surrounding these objects to look for associated supernova remnants.

We see from Table 1 that 10 of the 12 SGR/AXPs have proposed associations with radio shell SNRs. The probabilities of a chance coincidence for some of the individual associations have been estimated (e.g., Cline et al. 1982; Felten 1981; Kulkarni & Frail 1993) at a few times 10^{-2} or less (see the Appendix). The chance probability for an association between an SGR/AXP and an SNR can be estimated by simply considering the spatial density of known supernova remnants in the Galactic plane (in the following we assume that the localization error box of the SGR/AXP is small compared to the size of the SNR). For the extreme case, we consider just the SGRs and AXPs located in the highly crowded inner Galaxy. There all eight SGR/AXPs appear to have associated SNRs. These have Galactic longitudes of between 286° and 43° and latitudes within $\pm 1\overset{\circ}{.}2$. Within this area of 1.0×10^6 arcmin^2, there are 142 known SNRs (D. A. Green 2000, Catalogue of Galactic Supernova Remnants) covering a combined surface area of 3.4×10^4 arcmin^2, which is actually an overestimation due to overlap between the remnants. For a single association with the SGR or AXP displaced from the center of the remnant by as much as 2.3 times the remnant radius (as implied by the SGR 1627−41/G337.0−0.1 association), the chance association probability is roughly $2.3^2 \times 3.4 \times 10^{-2} \sim 18\%$, or $\sim 16\%$ correcting for overlap. Thus there is a significant probability that a single association might be simply a chance coincidence, if we relied solely on position, but the probability of getting even four chance associations out of eight tries is only 2%, and the probability that eight of eight are spurious is just 4×10^{-7}.

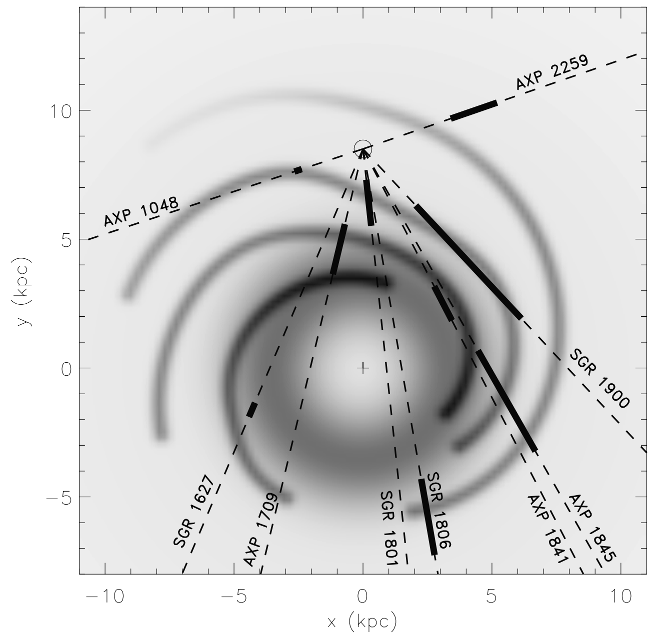

FIG. 1.—Positions of the soft gamma-ray repeaters (SGR) and anomalous X-ray pulsars (AXP) and their associated supernova shell remnants (SNR) projected onto a model (Taylor & Cordes 1993) of the Galactic plane distribution of free electrons. The position of the Galactic center and the Sun are marked by the plus signs and open circles, respectively, and the line of sight to each source is shown by a dashed line. The estimated distances to the sources, from Galactic kinematic arguments or association with molecular clouds or spiral arms, are shown by the heavy solid lines.

4. THE DISTANCES AND AGES OF THE ASSOCIATED REMNANTS

In order to probe the SGR/AXP environments, we need to know the radii of the associated SNR shells, which can be determined from their measured angular diameters, and their estimated distances. These distances are listed in Table 2 and discussed in the Appendix. All but three of the distances were determined from Galactic kinematic arguments based on interactions or associations with adjacent objects with known distances (e.g., H II regions or molecular clouds) or on absorption-line measurements. We did not use distances estimated from the standard SNR surface brightness/diameter relationships, because we did not want to bias the SNR sizes toward SNRs in the dense ISM, which is where most of the observed radio SNRs are located (e.g., Higdon & Lingenfelter 1980; Kafatos et al. 1980). SNRs expanding in the tenuous hot ISM become large and hard to detect (e.g., Duncan et al. 1997) much quicker than SNRs in dense environments and are underrepresented.

The positions of the Galactic SNRs associated with SGRs and AXPs are shown in Figure 1, projected onto a model of the Galactic plane distribution of free electrons (Taylor & Cordes 1993) that traces star formation regions delineating the spiral arms (e.g., Georgelin & Georgelin 1976). We see that the estimated distances of the SNRs are quite consistent with Galactic structure, placing them in or near the spiral arms where the bulk of recent massive star formation

TABLE 2

DISTANCE MEASURES OF GALACTIC SGRs AND AXPs AND ASSOCIATED SNRs[a]

SNR	l (deg)	b (deg)	Distance[b] (kpc)	DM[c] (pc cm^{-3})	SGR/AXP	N_H (10^{22} cm^{-2})
Kes 73	27.386	−0.006	6.0–7.5	440–620	AXP 1841−045	2.7–3.4
CTB 109	109.093	−0.993	3.6–5.5	100–135	AXP 2259+58.6	0.9–1.0
G29.6+0.1	29.679	−0.109	9.0–13.5[d]	860–1200	AXP 1845−0258	8.0–10.0
G337.0−0.1	336.968	−0.111	10.7–11.3	1020–1070	SGR 1627−41	6.8–8.0
G346.6−0.2	346.482	+0.035	3.0–5.0[d]	120–340	AXP 1709−40	1.7–1.9
G10.0−0.3	9.996	−0.242	13.0–16.0	1070–1200	SGR 1806−20	5.8–6.2
G42.8+0.6	43.021	+0.766	3.0–9.0[d]	70–460	SGR 1900+14	1.9–2.3
G287.8−0.5	288.257	−0.518	2.5–2.8	90–120	AXP 1048−5937	0.4–0.6

[a] See Appendix and references therein.
[b] Kinematic distance unless otherwise noted.
[c] Dispersion measures calculated from the model of Taylor & Cordes 1993.
[d] Adopted distance (see text).

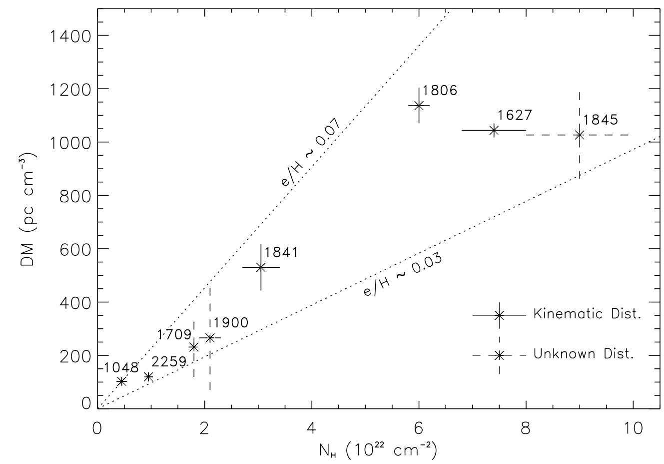

FIG. 2.—Inferred dispersion measure (Taylor & Cordes 1993) towards each of the SNRs, given the range of assumed distances, plotted against the observed N_H values for the X-ray absorption of their associated SGRs and AXPs. As shown by the dotted lines, the data are consistent with the typical range of Galactic electron-to-hydrogen ratios (*e*/H) (Spitzer 1978). This supports the association of SGRs/AXPs and SNRs by showing that the SNR distances are consistent with the SGR and AXP distances.

has occurred. We also see that the estimated distances of the SNRs are not systematically underestimated in our analysis, since five of nine SNR-AXP/SGR associations lie roughly at or beyond the distance of the Galactic center—as would be expected for a relatively unbiased sample of Galactic sources. This also shows that they are not likely to be systematically much farther away or most would lie on the other side of the Galaxy or even outside of the Galaxy.

To further test both the AXP/SGR-SNR associations and their estimated distances, we compare the electron column depth associated with the SNR distance with the H column depth determined from the X-ray absorption of the AXP/SGR emission. We calculate the dispersion measure to each source, given the assumed distances, and compare that to the measured N_H value for each source. Table 2 lists the distance ranges, calculated dispersion measures using the Taylor & Cordes (1993) model and observed N_H values for each SGR/AXP and associated SNR. The dispersion measure (DM) versus N_H is plotted in Figure 2. As seen from the figure, the data points are well correlated between lines representing free electron to hydrogen ratios $e/H = 0.03–0.07$, which is consistent with the range of $0.02-0.08$, which is expected from the mean mass fraction of ionized gas in the Galaxy of $\sim 1\%-5\%$ (e.g., Spitzer 1978). Thus we see that each of associations is consistent both in proximity of direction and in similarity of distance. This also shows that the estimated distances to the SGRs/AXPs and their associated remnants are not systematically underestimated. More information on the N_H values for each source is given in the Appendix.

The ages of the most of the SGRs and AXPs are much more uncertain than their distances. This is because the usual pulsar timing age formula—appropriate for pulsar spin-down due to MDR torque (although Gaensler & Frail 2000)—does not seem to be applicable for SGRs and AXPs, in general, because it yields age estimates that are inconsistent with the likely ages of the associated supernova remnants and the implied neutron star velocities for at least three of the sources (SGR 1806−20, SGR 1900+14, and AXP 2259+58.6) (Kouveliotou et al. 1998; Marsdenet al. 1999; and Corbet et al. 1995, respectively). In addition, all of the SGR and AXPs for which pulsar braking indices have been measured—AXP 1709−40 and AXP 2259+58.6 (Kaspi, Chakrabarty, & Steinberger 1999) and SGR 1806−20 (Woods et al. 2000)—have braking indices that are inconsistent with simple MDR spin-down. The MDR timing age for AXP 1841−045 of 4000 yr, however, is consistent with the estimated age of the associated SNR Kes 73 (Gotthelf, Vasisht, & Dotani 1999), but the braking index

TABLE 3

YOUNG RADIO PULSARS

Pulsar	Period (s)	Age[a] (kyr)	Distance[b] (kpc)	SNR	Radius[c] (pc)	Reference
J0534+2200......	0.033	1.3	1.5–2.5	...	>17	1
J1513−5908......	0.151	1.6	3.5–5.3	MSH 15−52	15–22	2
J0540−6919......	0.050	1.7	49.0–55.0	SNR 0540−693	8–9	3
J1614−5047......	0.232	7.5	3.7–11.0	...	>30	4
J1617−5055......	0.069	8.1	6.1–6.9	...	>30	5
J0835−4510......	0.089	11	0.4–0.6	Vela XYZ	15–23	11
J1341−6220......	0.193	12	4.0–13.0	G308.8−0.1	15–48	7
J1801−2451......	0.125	39–170	2.3–6.9	G5.4−1.2	10–30	8
J1803−2137......	0.134	16	2.9–4.9	...	>30	8
J1709−4428......	0.102	17	1.4–2.7	...	>30	2, 10
J1856+0113......	0.267	20	2.7–3.9	W44	12–17	9
J1048−5832......	0.124	20	2.2–3.7	...	>30	...
J1740−3015......	0.607	21	2.5–4.1	...	>30	6
J1826−1334......	0.101	22	3.1–5.2	...	>30	6
J1730−3350......	0.139	26	3.2–5.3	...	>30	...
J1646−4346......	0.232	32	3.4–10.3	G341.2+0.9	9–28	10

[a] Timing ages are from Taylor et al. 1993 and 1995 (unpublished), except for J1801−2451 (from Gaensler & Frail 2000).

[b] Distance from pulsar dispersion measure.

[c] Radius of SNR radio shell.

REFERENCES—(1) Frail et al. 1995; (2) Caswell et al. 1981; (3) Manchester et al. 1993; (4) Johnston et al. 1995; (5) Kaspi et al. 1998; (6) Braun et al. 1989; (7) Caswell et al. 1992; (8) Frail, Kassim, & Weiler 1994b; (9) Giacani et al. 1997; (10) Frail et al. 1994a; (11) Green 1984.

for this AXP has not yet been measured. We therefore adopt ages for the SGRs and AXPs based on the ages of their associated SNRs. Some of the associated remnants (N49, Kes 73, G29.6+0.1, and CTB 109) are relatively well-studied and have age estimates based on observed shock velocities and/or X-ray temperatures. For these remnants we take the minimum and maximum values for the ages of each remnant from the literature. For the rest of the associated SNRs, we adopt a lower age limit of $t_{\rm low} = \min[t_{\rm fe}, t_v]$, where $t_{\rm fe} = d_{\rm min}\theta_{\rm SNR}/v_{\rm ej}$ is the age of the remnant assuming free expansion, $d_{\rm min}$ is the minimum estimated distance, $\theta_{\rm SNR}$ is the SNR radius in radians, and $v_{\rm ej} \sim 10^4$ km s^{-1} is the maximum ejecta speed in free expansion. In addition, if we assume that the transverse velocity of the associated SGR or AXP cannot exceed $v_{\rm max}$, the minimum age is $t_v = d_{\rm min}\theta_*/v_{\rm max}$, where θ_* is angular offset of the pulsar from the center of the remnant. In this paper we will assume $v_{\rm max} = 2000$ km s^{-1}, which exceeds the observed velocity of any pulsar (e.g., Cordes & Chernoff 1998). For the upper age limit of the SNRs we choose 30 kyr, which is the maximum estimated age for the SNR/radio pulsar associations shown in Table 3.[4] For each SNR, we assume that the most likely age is the arithmetic mean of the age range, which is equivalent to assuming that the supernova rate is uniform in time throughout the Galaxy.

[4] The overall conclusions are unaffected if we instead choose 20 kyr (Braun, Goss, & Lyne 1989) for the maximum observable SNR age, as discussed in § 7.1.

5. THE DENSITIES OF SGR/AXP PROGENITOR ENVIRONMENTS

In Figure 3 we have plotted the SNR shell radii $R_{\rm SNR}$ as a function of the estimated age t of each remnant associated with an SGR or AXP. Overplotted with solid lines are simple approximations of the evolutionary tracks (Shull, Fesen, & Saken 1989) of supernova remnant expansion in a wide range of the external ISM densities n, assuming a total supernova kinetic energy of 10^{51} ergs. These SNR evolutionary tracks move through three phases: the initial free expansion/ejecta-dominated phase of the remnant, where the mass of the SN ejecta is much greater than the mass of the swept-up ISM and $R_{\rm SNR} \propto t$; the Sedov/adiabatic phase, which begins when the mass of the swept-up ISM is roughly greater than 10% of the mass of the SN ejecta and the remnant slows down with $R_{\rm SNR} \propto t^{2/5}$; and finally the radiative/snowplow phase, where the shell of swept-up ISM radiates away the energy of the remnant and it slows further with $R_{\rm SNR} \propto t^{2/7}$ (e.g., Shull et al. 1989). For individual supernova remnants, the tracks may differ by less than $\pm 15\%$ for a factor of 3 variation in supernova kinetic energies (Woosley & Weaver 1995). Also overplotted as dotted lines are the tracks of neutron stars born at the origin of the supernova explosion with varying velocities, showing the times required for them to catch up with the outer (radio) shell of the expanding remnant.

We see from Figure 3 that in spite of the uncertainties in the remnant ages and distances, all of the supernova shell remnants associated with SGRs and AXPs seem to reside in

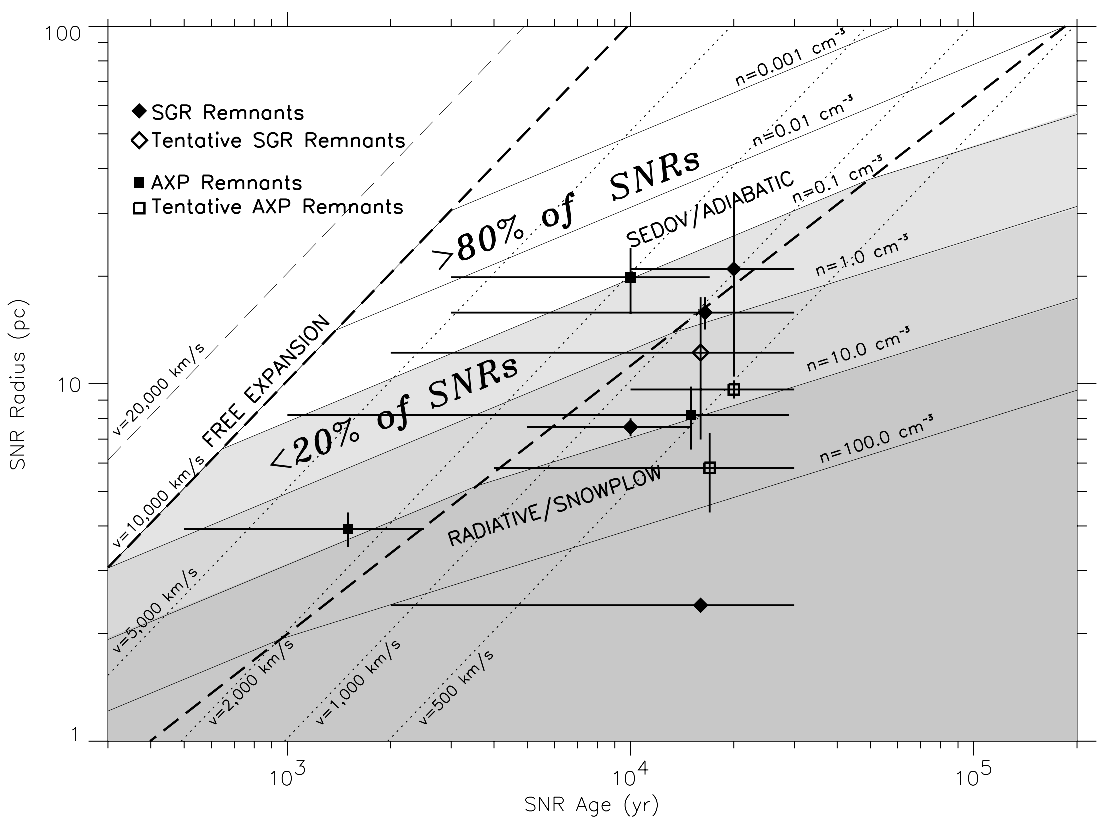

FIG. 3.—Radius of the SGR and AXP supernova remnant shells as a function of their age. The solid lines denote SNR expansion trajectories in the free expansion, Sedov, and radiative phases (*separated by dashed lines*), according to Shull et al. (1989), for an assumed supernova ejecta energy of 10^{51} ergs in a wide range of ISM densities. The dotted lines denote the tracks of neutron stars born at the origin of the supernova explosion with varying space velocities. The data show that these objects are unusual in that they are all preferentially formed in the denser (>0.1 cm^{-3}) phases of the interstellar medium (ISM), where less than 20% of all neutron-forming supernovae occur, as determined from observations of OB associations and Galactic supernova remnants.

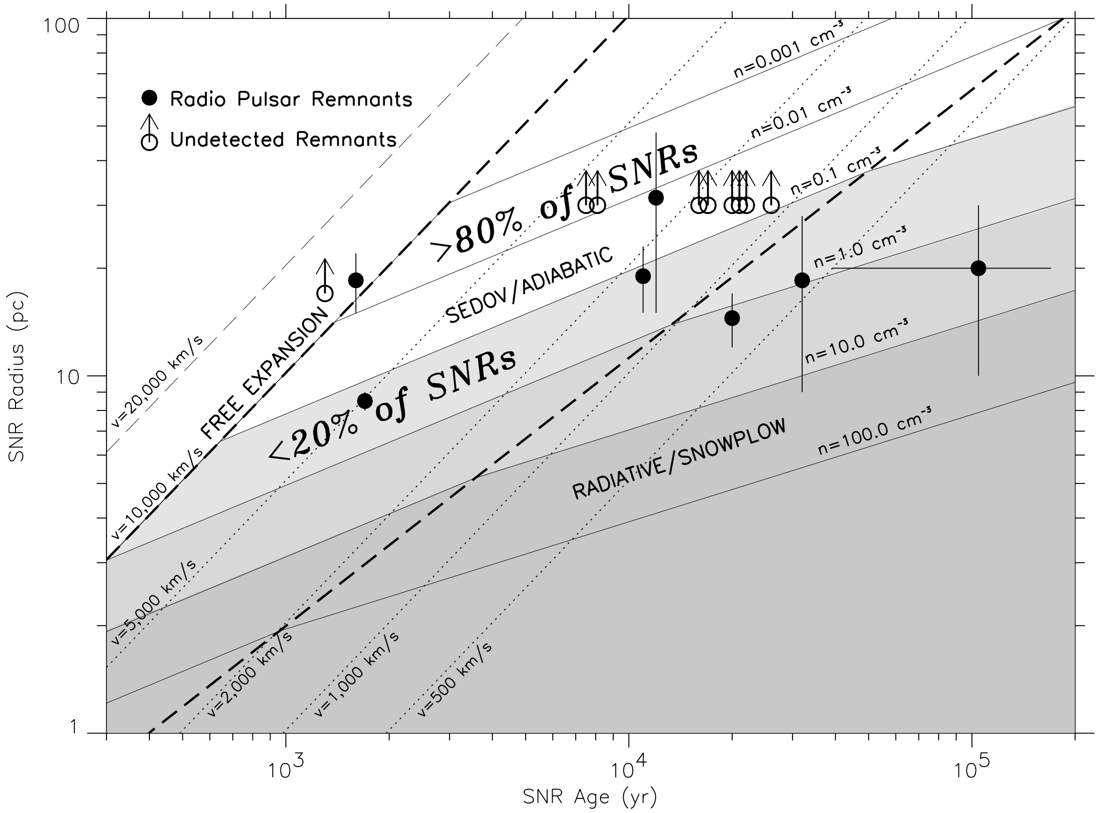

FIG. 4.— Same as Fig. 3, except for young radio pulsars with timing ages less than 32 kyr. The remnants for these pulsars reside primarily in the diffuse phase of the ISM, as expected from observations of OB associations and Galactic supernova remnants.

the denser ($n > 0.1$ cm^{-3}) phases of the ISM, where less than 20% of the neutron star–producing supernovae occur. Although the ages of the SNRs are highly uncertain, information on the progenitor ISM density can be extracted from the SNRs because densities inferred from the Sedov and radiative phase expansion formulae depend much more strongly on the SNR radii than on their ages. As we discuss in more detail below, the inferred distribution of progenitor ISM densities is not consistent with an origin of SGRs and AXPs that results from a purely intrinsic property of the neutron stars, because such stars should predominantly be born in the hot, diffuse ($n \sim 10^{-3}$ cm^{-3}) phase of the ISM,

TABLE 4

OCCURRENCES IN THE WARM AND HOT PHASES OF THE ISM

Source	Warm ISM (%)[a]	Hot ISM (%)[b]
Extragalactic SNe......	<20	>80
Galactic SNR	10 ± 10	90 ± 10
Young PSRs............	31 ± 14	69 ± 21
AXP/SGRs	83 ± 26	17 ± 12

NOTE—Extragalactic SNe: from van Dyk et al.'s 1996 observations of 49 extragalactic Type II and Ib/c SNe, corrected for detection threshold as discussed in text; Galactic SNR: from Higdon & Lingenfelter's 1980 analysis of the Clark & Caswell 1976 catalog of Galactic SNRs; young PSRs: the youngest (<30 kyr) pulsars (see Table 3 and Fig. 4); AXP/SGRs: see Table 1 and Fig. 3.

[a] Percentage in the warm ISM ($n \geq 0.1$ cm^{-3}).

[b] Percentage in the hot ISM ($n \sim 0.001$ cm^{-3}).

where more than 80% of the neutron star– and pulsar-producing SN occur. The probability of finding 10 such SNRs of 12 possible occurring in the denser ($n > 0.1$ cm^{-3}) phases of the ISM, when at most $\sim$20% are expected is only $\sim[12!/(10!2!)](0.2)^{10}(0.8)^2 \sim 4 \times 10^{-6}$. Even if we assume the maximum 16% probability for chance associations with SNR for all SGRs and AXPs *and* assume that all chance associations will be in denser ISM, the combined probability of any single, typical SNR being in the denser ISM is 0.33, equalling 0.2 naturally occurring plus 0.8×0.16 occurring by chance. Thus the probability of finding 10 of 12 possible occurring in the denser ISM is still only $\sim[12!/(10!2!)](0.33)^{10}(0.67)^2$, or $\sim 4 \times 10^{-4}$.

There are two obvious ways that the distribution of these SNRs might be made consistent with that of typical neutron stars and pulsars, i.e., 80% residing in the hot diffuse ISM and 20% in the dense ISM. One way would be if the SNR distances were systematically underestimated by roughly a factor of 3, but as we saw in Figures 1 and 2, that is not consistent with Galactic structure and would place roughly half of the SNRs well outside the Galaxy. Alternatively, exceedingly weak ($E \ll 10^{51}$ ergs) explosive energies for the SGR and AXP supernovae could in principle explain the unusually compact remnants associated with SGRs and AXPs, but this is inconsistent with the dynamical requirements of supernova explosions (e.g., Woosley & Weaver 1995) and the direct observations of SGRs and AXPs associated SNRs (e.g., Vancura et al. 1992; Rho & Petre 1997; Gotthelf & Vasisht 1997; Long et al. 1991). Moreover, there is direct evidence that at least eight of the 10 SGRs and AXPs associated SNRs are indeed in dense environments. OH maser emission, attributed to SNR shock interactions with molecular clouds, has been detected (Frail et al. 1996; Green et al. 1997) from molecular clouds thought to be associated with five of the SNRs (CTB 33, Kes 73, W28, G10.0−0.3, and G346.6−0.2). CTB 109 (e.g., Huang & Thaddeus 1985; Tatematsu et al. 1987), G287.8−0.5 (Jones 1973), and N49 (Hughes et al. 1984) also show evidence for molecular clouds associations. These associations with molecular clouds clearly show that the supernova remnant shells associated with SGRs and AXPs are expanding in high-density environments.

6. COMPARISON OF SGRs/AXPs TO YOUNG RADIO PULSARS

We can compare the observed properties of the SNRs associated with SGRs and AXPs with the remnants associated with another population of young neutron stars—the young radio pulsars listed in the catalogs of Taylor, Manchester, & Lyne (1993) and J. H. Taylor, R. N. Manchester, A. C. Lyne, & F. Camilo (1995, unpublished). We consider only the youngest pulsars, with timing ages less than ~ 30 kyr, whose ages are comparable to the age range in the SGR/AXP sample. The MDR timing ages of radio pulsars, unlike those for the SGRs and AXPs, are generally though to be good measures of their true ages (e.g., Cordes & Chernoff 1998), and we assume that the remnant ages are consistent with the MDR timing ages of their associated pulsars. A notable exception is PSR J1801−2451, which has an estimated age much greater than its MDR timing age (Gaensler & Frail 2000)—possibly indicating the presence of non-MDR spin-down torques in this pulsar. For the pulsar distances, we use the distances derived (Taylor et al. 1993; 1995, unpublished) from the measured dispersion and the Taylor & Cordes (1993) model of the free electron distribution in the Galaxy.

The supernova remnant shells of many of the young pulsars in Table 2 have not been detected in large-scale radio surveys of the Galactic plane (see e.g., Whiteoak & Green 1996; Reich et al. 1984; Duncan et al. 1997) or in deep radio observations of the fields surrounding young pulsars (e.g., Braun, Goss, & Lyne 1989; Frail, Goss, & Whiteoak 1994a). For these pulsars, we found no likely associated SNRs in the Green (2000) catalog within a search radius corresponding to a transverse velocity of as much as 2000 km s^{-1}, assuming the estimated distances and timing ages for these sources listed in Table 1. Since the Green (2000) SNR catalog is more or less complete (Whiteoak & Green 1996) down to a limiting surface brightness, the missing SNRs for these objects have probably expanded such that their surface brightnesses have faded below the limiting surface brightness of the radio surveys of the Galactic plane. We therefore assume that the radio shells of the remnants associated with these pulsars (except for the Crab, for which we use a lower limit of 17 pc for the remnant radius; Frail et al. 1994a) have expanded beyond this detectability threshold, and following Braun et al. (1989) we assign lower limits of 30 pc to the undetected remnants corresponding to these pulsars. The observed and derived parameters for the young radio pulsars are listed in Table 3, with references to the timing data, distances, and SNR shell radii. A plot of the supernova remnant shell radii versus age for the radio pulsars is shown in Figure 4.

We clearly see from Figure 4 that most of the young pulsars appear to have been born in the hot, diffuse phase of the ISM, as expected from other observations of their O and B star progenitors and their environments, as was discussed in the preceding section. Only ~ 5 of the 16 young pulsars have SNRs that may be expanding in the denser phases ($n > 0.1$ cm^{-3}) of the ISM, which is consistent with the expected fraction of $\sim 20\%$ or less despite the small number statistics. These results are summarized in Table 4.

7. DISCUSSION

7.1. *The Significance of the Environmental Evidence*

As seen from Figures 3 and 4, the SGRs and AXPs appear to form in denser regions of the interstellar medium than the sample of young radio pulsars. The significance of the apparent disparity between the SGR/AXP and radio pulsar environments can be evaluated by using "survival analysis" (Miller 1981) methods, which are statistical techniques incorporating "censored" data (e.g., upper limits) into data analysis. We first convert the age and SNR radii values of Tables 1 and 2 to ambient ISM densities n using the standard formulae in Shull (1983) and values for each age and SNR radius midway between the range of values listed in the tables. A total supernova kinetic energy of 10^{51} ergs was assumed for both the SGR/AXPs and radio pulsars. The lower limits on the radii of the undiscovered SNRs in Table 2 therefore became upper limits on the ambient densities for these SNRs.

The resulting distributions of n for the SGR/AXPs and radio pulsars were then tested for consistency with a single parent sample using the statistical analysis package ASURV Rev 1.2 (Lavalley, Isobe, & Feigelson 1992), which implements the methods presented in Feigelson & Nelson (1985). The two-sample univariate nonparametric tests used to compare the distributions consisted of two versions of the Gehan's generalized Wilcoxon test (permutation and hypergeometric variances), the logrank test, and the Peto & Peto and Peto & Prentice generalized Wilcoxon tests (see Lavalley et al. 1992 and references therein; Miller 1981; Feigelson & Nelson 1985). These methods differ in their assumptions regarding the censoring process and in the ways that they weight the data, but we found that they gave results that were consistent to within 2 orders of magnitude. We use the statistical tests to compute the probability $P_{\rm same}$ that the distribution of n for the SGRs and AXPs is consistent with the same distribution for the young radio pulsars. For the full sample of SNR associations in Table 1 we calculate $P_{\rm same} = 9 \times 10^{-5}$–$6 \times 10^{-4}$. If we exclude from the sample the objects with tentative SNR associations—SGR 1801−23 and AXPs 1709−40 and 1048−5937—we find $P_{\rm same} = 1 \times 10^{-4}$–$8 \times 10^{-4}$. Finally, if we change the maximum possible remnant age from 30 to 20 kyr (Braun, Goss, & Lyne 1989), we obtain $P_{\rm same} = 5 \times 10^{-4}$–$3 \times 10^{-3}$ for the full set of SNR associations in Table 1, and $P_{\rm same} = 8 \times 10^{-4}$–$5 \times 10^{-3}$ if we exclude the tentative SNR associations. The data therefore support the conclusion that the progenitors of SGRs and AXPs exploded in denser environments than the progenitors of radio pulsars.

This conclusion can be alleviated only if one assumes that a large fraction of the previously claimed SNR associations with AXPs and SGRs are spurious *and* that the remnants truly associated with these objects have large diameters and are currently undetected. As discussed in § 3, however, it is unlikely that more than a couple of the associations in Table 1 are spurious, given the distribution of supernova remnants in the Galactic plane. At least five of the SNR associations in Table 1 would have to be spurious before one could conclude that the evidence for dense SGR and AXP progenitor environments was insignificant (i.e., the probability $P_{\rm same} > 0.01$). The association of SGR 1900+14 with SNR G42.8+0.6 has been questioned since the recent discovery (Lorimer & Xilouris 2000) of a 40 kyr old pulsar PSR J1907+0918 equally close ($\sim 20'$) to the SNR, and the discovery (Vrba et al. 2000) of a compact cluster of massive stars at an estimated distance ranging from 12 to 15 kpc, and only $\sim 10''$ from the SGR 1900+14 line of sight. The relatively low H column depth from absorption in the SGR's X-ray spectrum (Hurley et al. 1999b; Woods et al. 1999a) clearly implies (e.g., Fig. 2) a distance closer to 5 kpc, so that the SGR and SNR may not be related to the cluster. If SGR 1900+14 is associated with the compact cluster at the more extreme distance, Vrba et al. (2000) suggest an association with a possible compact (<1 pc diameter) SNR indicated by the local diffuse X-ray emission. This new SGR/SNR association would therefore imply a much greater SGR 1900+14 progenitor density than the G42.8+0.6 association, increasing the evidence for dense progenitor environments for SGRs. A similar compact (<1.0 pc diameter) cluster of massive stars has also been observed (Fuchs et al. 1999) to be coincident with SGR 1806−20 and G10.0−0.3. In addition, AXP 1048−5937 and its associated SNR G287.8−0.5 are associated with the Carina star-forming region (Thé & Vleeming 1971; Seward & Chlebowski 1982). In these cases the associations with the clustered star formation regions are quite consistent with the SGR/SNR associations, since the distances of the star-forming regions and the SNRs are comparable.

7.2. *SGRs and AXPs as Magnetars*

The unusual properties of SGRs and AXPs may be due to the fact that they have unusually strong magnetic fields, as in the magnetar model (Duncan & Thompson 1992; Thompson & Duncan 1993, 1995, 1996). In the context of this model, it has been suggested that the association of SGRs and AXPs with dense progenitor environments may be explained by a selection effect in the following manner. Magnetars are thought to form from progenitor stars with high angular momenta, such that the superstrong (10^{14}–10^{15} G) magnetic field can be generated in the proto–neutron star by dynamo action just after core collapse (Duncan & Thompson 1992). Since the total stellar angular momentum $J \propto MRv_R$ (assuming rigid rotation, where v_R is the observed rotational velocity), one might expect the largest and most massive stars to be the likely progenitors of magnetars. Furthermore, since the main-sequence lifetimes of stars decrease with increasing mass, the more massive stars would be the first to become supernovae—therefore exploding into more dense surroundings before the parent molecular cloud has been cleared by the successive supernovae of less massive stars.

The two basic assumptions of this scenario do not appear to be consistent with observations. First, the observed stellar rotation velocities (e.g., Drilling & Landoldt 2000) show that the angular velocity Ω increases with stellar mass only up to about 2 $M_\odot$ and then *decreases* with increasing mass, dropping to only 20% of its maximum value for stellar masses greater than 25 $M_\odot$. One would therefore expect the precollapse cores of the most massive stars to have less angular momenta than the cores of less massive supernova progenitors. This is supported by detailed calculations of the stellar evolution of rotating massive stars up to the time of core collapse (Heger, Langer, & Woosley 2000), which indicate that the final angular momentum of the core region is less for a massive star than for a less massive star with the same initial rotation rate. This is due to the greatly increased mass loss of luminous massive stars, which shed angular momentum in their powerful stellar winds (e.g., Heger et al. 2000).

Second, the supernovae of massive stars would still not be expected to all explode in the denser medium, because star formation in massive ($>10^5$ $M_\odot$) clouds is episodic through several generations (e.g., McKee & Williams 1997). These successive generations commence roughly every $\sim$4–5 Myr, over a period of $\sim$20–30 Myr, each producing roughly 10^3 O and B star supernova progenitors. Each subsequent generation of star formation commences shortly after the onset of supernova explosions from the previous generation, at the end of their main-sequence lifetimes of more than 3 Myr. Therefore only the most massive stars in the first generation of star formation in a new star-forming region would be expected to explode in denser environments, and the subsequent generations of massive stars should be born in the same low-density superbubble environment as the population as a whole. Thus even if magnetars were produced by the most massive stars, we still would not expect more than a small fraction of them to explode in the denser phases of the ISM.

7.3. *Propeller-based Models for SGRs and AXPs*

The rapid spin-down rates, ages, clustered spin periods, and X-ray luminosities of AXPs and/or SGRs can all be explained by models involving the propeller effect as the dominant spin-down torque (van Paradijs et al. 1995; Alpar 2000; Chatterjee et al. 2000; Chatterjee & Hernquist 2000). In the context of these models, SGR bursts can be explained in terms of solid-body accretion (Hartwitt & Salpeter 1973; Tremaine & Zytkow 1986) or crustal instabilities (Blaes et al. 1990). Because there are upper limits on the masses of the possible binary companions of at least some of the AXPs (e.g., Mereghetti et al. 1998), the accreted material is probably ejecta from the neutron star's own supernova explosion (van Paradijs et al. 1995; Corbet et al. 1995). In addition, since some of the SGRs and AXPs are located outside their apparent supernova remnants, the accreted material must form an accretion disk that can store the angular momentum of the accreted material and spin-down the neutron star on timescales of 1–10 kyr. Upper limits on the disk emission from the nearby AXP 2259+58.6 (Coe & Pightling 1998; Hulleman et al. 2000) may rule out a standard hydrogen accretion disk around this AXP, but a disk may still exist given the uncertainties in the spectra of disks formed from metal-rich supernova ejecta and dust (e.g., Perna, Hernquist, & Narayan 2000). In addition, the noisy spin-down of SGR 1806−20 (Woods et al. 2000) and the 6.4 keV emission feature (Strohmayer & Ibrahim 2000) observed from an SGR 1900+14 burst are both consistent with accretion disks around these objects. There are three possible scenarios involving accretion from the ejecta of the supernova explosion that produces the neutron star: "fallback" disk accretion, "pushback" disk accretion, and accretion involving high-velocity neutron stars.

It was recently proposed that AXPs may be formed from neutron stars accreting material from fallback accretion disks (Chatterjee et al. 2000; Chatterjee & Hernquist 2000). These disks may be formed from ~ 0.001–$0.1\ M_\odot$ (Michel 1988; Lin, Woosley, & Bodenheimer 1991) of inner ejecta material less than 2 hr after the initial core collapse in a Type II supernova explosion (e.g., Chevalier 1989; Woosley & Weaver 1995). Since a total accreted mass of only 10^{-6} $M_\odot$ is required to explain the spin-down of SGRs and AXPs via the propeller mechanism (e.g., Alpar 2000; Chatterjee et al. 2000; Chatterjee & Hernquist 2000), only a very small fraction ($\sim 10^{-5}$) of the fallback material must be accreted into a disk for this model to explain the spin-down rates and ages of the SGRS and AXPs. Formation of such a fallback disk is limited to less than 7 days after the core collapse because of heating of the ejecta by ^{56}Ni (Chevalier 1989). This is long before the remnant feels the external environment early in the Sedov phase, and therefore formation of an early fallback disk may not be compatible with the evidence for dense SGR and AXP progenitor environments.

A model involving fallback disks that form later in the evolution of the SNR, however, could be consistent with the evidence of dense SGR and AXP environments. In particular, the expansion of slow-moving ejecta can be reversed by the Sedov phase reverse shock resulting from the interaction between the blast wave and the external medium (e.g., McKee 1974; Truelove & McKee 1999), and the subsequent implosion could result in the formation of a pushback disk—so named because the SNR ejecta is pushed-back onto the star because of the interaction with the dense environment surrounding the progenitor. Pushback disk formation would probably be most likely for (1) neutron star progenitors that experienced a large amount of mass loss prior to becoming supernovae and (2) progenitors in the dense ISM, which would provide the necessary pressure to confine the wind mass near the star. This is exemplified by the circumstellar environments surrounding the progenitor of SN 1987A, which is surrounded by $n \sim 10^2$–10^3 cm^{-3} in wind material and H II gas (e.g., Chevalier & Dwarkadas 1995). The pushback process begins at the "reversal time" $t_{\rm rev} \sim 0.5$–1.0 kyr (Truelove & McKee 1999), and the pushback mass is $\sim 0.4\ M_\odot$ given a total ejecta mass of $10\ M_\odot$. As with the fallback disks discussed above, the formation of a pushback disk from only a small fraction of this matter would be required to explain the spin-down of SGRs and AXPs. Since this later fallback occurs after the majority of ^{56}Ni and ^{56}Co decays, the formation of the accretion disk around the neutron star would not be limited by radioactive heating. Such a model may be a plausible explanation for the dense SGR and AXP environments and needs to be explored in more detail.

The final propeller-based scenario for SGRs and AXPs involves high-velocity neutron stars (HVNSs) capturing disk material from comoving supernova ejecta, as first suggested van Paradijs, Taam, & van den Heuvel (1995). Although the exact mechanism by which neutron stars are given substantial "kick" velocities at birth is not known, observations show that the kick velocities exceed 500 km s^{-1} in approximately 20% of all neutron stars (Cordes & Chernoff 1998). In addition, this kick velocity appears to be independent of the dipole moment of the neutron star, as indicated by population studies of isolated radio pulsars (Cordes & Chernoff 1998; Deshpande, Ramachandran, & Radhakrishnan 1999) and observations of extremely high velocity stars with canonical neutron star magnetic fields of $\sim 10^{12}$ G (e.g., PSR B2224+65; Romani, Cordes, & Yadigaroglu 1997). As implied by the ratio $\theta_*/\theta_{\rm SNR}$ listed in Table 1, many of the SGR/AXP positions are significantly displaced from the apparent centers of their associated SNRs. These displacements imply that the SGR/AXPs may have systematically large transverse velocities, although there is considerable uncertainty in the actual velocities, mainly because of uncertainties in the ages of the associated remnants. In addition, the actual space velocities of the SGR/AXPs are larger by an unknown factor dependent on the viewing angle. It has been estimated (van Paradijs et al. 1995) that a $10^{-4}\ M_\odot$ accretion disk may be acquired by a high-velocity neutron star as it moves through nearly comoving supernova ejecta. However, detailed calculations of the time-dependent accretion rate for the range of ISM densities, progenitor mass loss parameters, and neutron star magnetic fields, initial spin periods, and velocities are needed to properly constrain such a model. This is beyond the scope of the present paper and will be left for future work.

Additional evidence in favor of the pushback disk and HVNS models for SGRs and AXPs may be provided by the observed number of these sources. For the pushback disk model, the number of SGRs and AXPs less than t years old is given by $N = r_b\, f_w\, f_{\rm env}\, t$, where r_b is the Galactic neutron star birthrate, $f_{\rm env}$ is the fraction of neutron star progenitors in the warm dense ISM, and f_w is the fraction of neutron star progenitors that experience mass loss sufficient to form a pushback disk in dense ISM environments. Since the rate of mass loss from stellar winds is an increasing function of the initial main-sequence mass, the fraction f_w can be estimated by considering the *minimum* stellar mass that undergoes presupernova mass loss sufficient to decelerate its supernova ejecta at early times. To first order, this should occur when the total wind mass emitted during the progenitor's life is approximately equal to the supernova ejecta mass. From the solar metallicity stellar models of Schaller et al. (1992)—which include mass loss—this occurs for stars of initial main-sequence masses greater than $M_{\rm min} \sim 27$ $M_\odot$. Using $M_{\rm min}$ and a Salpeter IMF with a maximum and minimum neutron star progenitor mass of 40 and 8 $M_\odot$, respectively (Woosley & Weaver 1995), we obtain $f_w \sim 0.1$. Assuming $f_{\rm env} < 0.2$ (as discussed in § 2) and $r_b \sim 1/40$ yr^{-1} (van den Bergh & McClure 1994), we obtain $N < 15$ SGRs and AXPs with ages less than $t = 30$ kyr. This is similar to the observed number (12) of these sources, which can be taken as evidence supporting the pushback disk model. A similar calculation is possible for the HVNS model. In this case, the expected number of SGRs and AXPs less than t years old is given by $N = r_b\, f_{hv}\, f_{\rm env}\, t$, where f_{hv} of neutron stars with high space velocities and r_b and $f_{\rm env}$ are defined as before. Using the same values of $f_{\rm env}$ and r_b, and assuming $f_{hv} \sim 0.2$ (velocities greater than 500 km s^{-1}; Cordes & Chernoff 1998), yields $N \sim 30$ expected SGR and AXP sources with ages less than 30 kyr for the HVNS model. Again, these numbers are in the right ballpark for the observed numbers of SGRs and AXPs.

8. SUMMARY

We have shown that soft gamma-ray repeaters and anomalous X-ray pulsars are born in regions of the interstellar medium that are denser than the environments typical of young neutron stars. This suggests that the development of SGRs and AXPs may be related to their environments, and we examine the implications of this on magnetar and propeller-based models for SGRs and AXPs. The evidence of dense progenitor environments would be consistent with the magnetar model only if magnetars are born exclusively in dense environments, which does not appear to be the case if magnetars form only from the most massive stars. Propeller-based models for SGRs and AXPs involving the formation of accretion disks from supernova ejecta appear to be consistent with the evidence for dense progenitor environments since these environments may induce the formation of such disks. This may occur in two ways. *Push-back* disks may be formed from the infall of the innermost ejecta, pushed back toward the neutron stars by prompt reverse shocks from the interactions of the expanding remnants with massive progenitor winds confined close to the stars by dense surrounding gas—producing rapid deceleration of the expanding ejecta and strong prompt reverse shocks (Truelove & McKee 1999). Fossil disks may also form around high-velocity neutron stars accreting from nearly comoving supernova ejecta, slowed by the strong prompt reverse shocks in such dense environments (van Paradijs et al. 1995).

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APPENDIX

NOTES ON INDIVIDUAL SGRs AND AXPs

Here we discuss and reference the SNR distances, radii, and ages listed in Tables 1 and 2. The SNRs associated with all but three of the SGRs and AXPs have kinematic distances derived from associations with objects (e.g., H II regions or molecular clouds) having known distances. The distances of the other three SNRs—G29.6+0.1, G346.6−0.2, and G42.8+0.6—are derived from consideration of Galactic spiral arms along the line of sight. The remnants Kes 73, N49, W28, and CTB 109 have published age estimates based on measurements of shock velocities and/or X-ray temperatures, and for these remnants we adopt an age range corresponding to the minimum and maximum values quoted in the literature. The rest of the associated remnants have no published age estimates other than those determined by assuming Sedov expansion and distances determined from Σ-D relations, which are biased toward denser phases of the ISM. For these SNRs we adopt a broad range of possible ages. We take a lower age limit of $t_{\rm low} = \min[t_{\rm fe}, t_v]$, where t_{fe} and t_v are the minimum ages derived by assuming free expansion of the SNR (at 10^4 km s^{-1}) and a maximum SGR/AXP transverse velocity of 2000 km s^{-1}, respectively. For an upper age limit, we take 30 kyr, which is the maximum estimated age for a SNR/radio pulsar association in Table 3. Finally, the hydrogen column densities ($N_{\rm H}$, listed in Table 2) are determined from the best-fit spectral models for the X-ray spectra of the SGRs/AXPs.

AXP 1841−045.—This AXP is coincident with the SNR G27.4+0.0 (Kes 73), which is estimated from the X-ray temperature to be 0.5–2.5 kyr old (Helfand et al. 1994; Gotthelf & Vasisht 1997). The diameter of the radio remnant is ∼4′ (Kriss et al. 1985), and the distance from H I absorption is estimated to be 6.0–7.5 kpc (Sanbonmatsu & Helfand 1992). A power-law fit to the X-ray spectrum of the AXP yields a best-fit value of $N_{\rm H} = (2.7\text{–}3.4) \times 10^{22}$ cm^{-2} (Gotthelf & Vasisht 1997), which is consistent with such a distance (see Fig. 2) and the $N_{\rm H}$ of $\sim 2 \times 10^{22}$ cm^{-2} found (e.g., Vasisht & Gotthelf 1997) of the X-ray spectrum of the SNR.

SGR 0526−66.—The error box of the SGR lies within the supernova remnant N49 (Evans et al. 1980; Cline et al. 1982), located in the LMC at a distance of 49–55 kpc (Feast 1991; Capccioli et al. 1990) and interacting with a molecular cloud (Hughes, Bronfman, & Nyman 1989). The diameter of N49 is ∼1′, and its estimated age is 5–16 kyr (Vancura et al. 1992; Shull 1983).

AXP 2259+58.6.—The AXP lies within the ∼30′ diameter (Hughes et al. 1984) SNR CTB 109 (G109.2−1.0). The distance to the remnant, as determined by spectroscopy of stars in nearby H II regions, is in the range 3.6–5.5 kpc (Rho & Petre 1997). The estimated remnant age is 3.0–17.0 kyr (Parmar et al. 1998; Hughes, Harten, & van den Burgh 1981), and there is evidence for interaction between CTB 109 and surrounding molecular clouds (e.g., Tatematsu et al. 1987). The best-fit model to the X-ray spectrum of the AXP yields $N_{\rm H} = (0.9\text{–}1.0) \times 10^{22}$ cm^{-2} (Parmar et al. 1998), which agrees with the range of $N_{\rm H} = (0.9\text{–}1.1) \times 10^{22}$ cm^{-2} found for the X-ray spectra from various parts of the remnant (Rho & Petre 1997).

AXP 1845−0258.—This AXP lies within the 5′ diameter remnant G29.6+0.1 (Gaensler et al. 1999). There are no kinematic distances, and the distance estimated from Galactic structure (see Fig. 1) is 9.0–13.5 kpc. This is consistent (see Fig. 2) with the AXP X-ray absorption of $N_{\rm H} = (9 \pm 1) \times 10^{22}$ cm^{-2} (Torii et al. 1998). There are no reliable SNR age estimates, so we adopt an SNR age range of 0.6–30.0 kyr by taking the limits of free expansion and the maximum detected SNR age from the radio pulsar sample. The chance association probability between the AXP and the SNR is estimated to be 1.6×10^{-3} (Gaensler et al. 1999).

SGR 1627−41.—This SGR was first associated with the SNR G337.0−0.1 by Hurley et al. (1999c). The distance to this remnant is estimated to be 11.0 ± 0.3 kpc (Corbel et al. 1999), based on an association with a giant molecular cloud within the star-forming region CTB 33. The angular diameter of SNR G337.0−0.1 is ∼1.′5 (Corbel et al. 1999). The SNR age is unknown, so we adopt an age of 2.6–30.0 kyr. The probability that the SGR/SNR association is spurious was estimated to be ∼5% (Smith, Bradt, & Levine 1999). A marginal detection of a 6.4 s pulsation from the SGR was reported (Woods et al. 1999b) but not confirmed by subsequent observations (Hurley et al. 2000b). The X-ray spectrum of the SGR is equally well fitted by power-law, blackbody, and thermal bremsstrahlung functions (Hurley et al. 2000b), and the mean $N_{\rm H}$ for the power-law spectral fit is $(7.4 \pm 0.6) \times 10^{22}$ cm^{-2} (Woods et al. 1999b; Hurley et al. 2000), which is consistent with the SNR distance (see Fig. 2).

SGR 1801−23.—The most recently discovered SGR, this source has a long and thin error box (Cline et al. 2000) that passes through the center of SNR W28 (G6.4−0.1). W28 is associated with OH masers in a molecular cloud whose distance rules out its previously suggested association with PSR B1758−23 (Claussen et al. 1997). W28 has a radio diameter of ∼40′ (Andrews et al. 1983) and an estimated age of 2.4–30.0 kyr (Long et al. 1991), and it is located at a distance of 1.2–3.0 kpc (Clark & Caswell 1976; Goudis 1976). The low energy absorption in the X-ray spectrum of W28 is $N_{\rm H} = (0.5 \pm 0.1) \times 10^{22}$ cm^{-2} (Rho & Petre 1998), but there is no $N_{\rm H}$ estimate for the SGR since its burst spectra were not measured to low enough energy to determine a value and the persistent low-energy X-ray counterpart of the source has not yet been identified.

AXP 1709−40.—This AXP lies ∼8′.5 form the center of the ∼10′ diameter (Whiteoak & Green 1996) remnant G346.6−0.2. The chance association probability between the AXP and this remnant is ∼0.1, from the method of § 3. There are no published age estimates for the SNR, so we derive and age range of 3.6–30.0 kyr from the transverse velocity and maximum SNR age limits. There is no kinematic distance estimate to the SNR, so we adopt a distance of 3–5 kpc, which agrees with Galactic structure arguments placing it in or near spiral arms. This distance is also consistent (Fig. 2) with the AXP X-ray absorption of $N_{\rm H} = (1.81 \pm 0.07) \times 10^{22}$ cm^{-2} (Sugizaki et al. 1997).

SGR 1806−20.—This SGR lies within the ∼7′.5 diameter (Kulkarni et al. 1994) remnant G10.0−0.3, which is located at a distance of 14.5 ± 1.4 kpc as determined from CO line observations of maser-associated molecular clouds (Corbel et al. 1997). This distance is consistent (Fig. 2) with the large column density $N_{\rm H} = (6.0 \pm 0.2) \times 10^{22}$ cm^{-2} found (Sonobe et al. 1994) for the X-ray spectrum of the SGR. The chance SGR/SNR association probability has been estimated at $\sim 5 \times 10^{-3}$ (Kulkarni & Frail 1993). The age is unknown, so we adopt an age of 3.5–30.0 kyr. This SGR and SNR may be associated with a compact cluster of stars (Fuchs et al. 1999).

SGR 1900+14.—This SGR has been associated (e.g., Hurley et al. 1999a) with the 24′ diameter remnant SNR G42.8+0.6 (Fürst et al. 1987) from whose center it is displaced by 17′. No kinematic distances to the SNR are available, so we adopt a distance of 3–9 kpc from association with a Galactic spiral arm (Fig. 1). This distance is also consistent (see Fig. 2) with the mean value of the SGR X-ray absorption for the best-fit spectral model: $N_{\rm H} = (2.1 \pm 0.2) \times 10^{22}$ cm^{-2} (Woods et al. 1999a). The age of the remnant is unknown, so we adopt an age range of 9.6–30.0 kyr. The chance probability of the SGR/SNR association by the method of § 3 is ∼0.1. This SGR has also been associated (Vrba et al. 2000) with a compact star cluster at a distance of anywhere from 5 to 15 kpc, although the relatively low value of $N_{\rm H}$ from the absorption in the SGR X-ray spectrum (Hurley et al. 1999b; Woods et al. 1999a) favors the near end of the range.

AXP 1048−5937.—This AXP is situated near the ∼25′ diameter remnant G287.8−0.5 (Jones 1973) associated with the Carina star-forming region at a distance of 2.5–2.8 kpc (Thé & Vleeming 1971; Seward & Chlebowski 1982). The geometrical chance association probability (§ 3) between the AXP and the remnant is ∼0.16. There are no age estimates of the SNR, and therefore we derive an age of 9.8–30.0 kyr from the transverse velocity limit and the maximum detectable SNR age. The best-fit spectral model of the AXP emission yields the low value of $N_{\rm H} = (0.45 \pm 0.10) \times 10^{22}$ cm^{-2} (Oosterbroeck et al. 1998), which is consistent (e.g., Fig. 2) with the SNR/Carina distance.

AXP 0720−3125.—Despite its low X-ray luminosity ($\sim 5 \times 10^{31}$ ergs s^{-1}, Haberl et al. 1997), this 8.39 s pulsar has been included in the AXP sample because of its spin period, lack of an optical counterpart (Motch & Haberl 1998), and fast spin-down rate ($\sim 3 \times 10^{-12}$, Haberl et al. 1997). Although there is no adjacent SNR in the catalog of Green (2000), the low X-ray absorption indicates a distance of only 0.10 ± 0.02 kpc (Haberl et al. 1997) to the source, which makes the detection of its associated SNR unlikely (see § 3) if its age is as great (∼40 kyr) as that indicated by its spin-down rate.

AXP 0142+615.—This apparently old (possibly ∼60 kyr) and well-studied (e.g., White et al. 1996; Israel et al. 1994 and references therein) AXP has no remnant within ∼1° of it in the Green (2000) catalog. But there is evidence (White et al. 1996) that this source is in or behind a giant molecular cloud. Given the rapid evolution (e.g., Truelove & McKee 1999) and possible self-absorption (Reynolds 1988) of the radio emission of SNRs in dense environments, the associated SNR may have faded below detectability, and therefore we are unable to constrain the radius of the associated remnant.

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Note added in proof.—We have been alerted by B. Gaensler that AXP 1709−40 is approximately twice as far from SNR G346.6−0.2 than indicated in Table 1, and therefore this association is probably spurious. As discussed in § 7.1, however, the elimination of his SNR association does not alter the conclusions of this paper.