ANOMALOUS X-RAY PULSARS AND SOFT GAMMA-RAY REPEATERS — THE CONNECTION WITH SUPERNOVA REMNANTS

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ABSTRACT

Many of the properties of anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs) are still a matter of much debate, as is the connection (if any) between these two groups of sources. In cases where we can identify the supernova remnant (SNR) associated with an AXP or SGR, the extra information thus obtained can provide important constraints as to the nature of these exotic objects. In this paper, I explain the criteria by which an association between a SNR and an AXP/SGR should be judged, review the set of associations which result, and discuss the implications provided by these associations for the ages, environments and evolutionary pathways of the AXPs and SGRs. There are several convincing associations between AXPs and SNRs, demonstrating that AXPs are young neutron stars with moderate space velocities. The lack of associations between SGRs and SNRs implies that the SGRs either represent an older population of neutron stars than do the AXPs, or originate from more massive progenitors.

INTRODUCTION

The anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs) both represent exotic populations of neutron stars, distinct from more typical core-collapse products such as radio pulsars or X-ray binaries. We have learnt a great deal about SGRs and AXPs through their timing, photometric and spectroscopic properties — the consensus from these studies is that the SGRs, and most likely the AXPs also, are "magnetars", neutron stars with surface magnetic fields $10^{14} - 10^{15}$ G (see reviews by Hurley 2001 and Mereghetti et al. 2003, and contributions in these proceedings by Woods and by Kaspi).

However, direct observations of AXPs and SGRs have as yet provided little data on their distances, ages, space velocities, lifetimes, birthsites and progenitors, all of which provide crucial information on the demographics and evolution of these interesting sources. In this review, I discuss how we can obtain indirect information on these issues by associating AXPs and SGRs with supernova remnants, star clusters and molecular clouds.

ASSOCIATIONS WITH SUPERNOVA REMNANTS

Associations between neutron stars and supernova remnants (SNRs) can provide unique information about core-collapse supernovae and their aftermath. Over the last 35 years, there have been many controversial and colourful discussions about various radio pulsars and their associations (or lack thereof) with SNRs. Consequently, a considerable amount of collective wisdom has been accumulated as to how to best judge a potential association. Important criteria for considering an association include:

- **Evidence for interaction.** If a pulsar and a SNR can be shown to be interacting (e.g. if a pulsar is in the process of penetrating the shell of a SNR; Shull et al. 1989), this provides a very strong case for a physical association.
- **Consistent distances/ages.** Pulsar distances are usually estimated by comparing the dispersion of pulses with a model for the Galactic electron distribution, while a pulsar’s characteristic age is $\tau_c = P/2\dot{P}$ (where $P$ is the pulsar’s spin-period and $\dot{P}$ is the period derivative). SNR distances are most often determined from $\text{H}_1$ absorption measurements, while SNR ages can be estimated from their spectral properties or from an association with a historical supernova. For a genuine association, agreement between the pulsar’s and SNR’s distances are expected, and agreement in their ages is encouraging also.

- **Inferred transverse velocity.** If we assume that a neutron star was born at the geometric centre of a coincident or nearby SNR, then the offset of the pulsar from the SNR’s centre can be combined with an age estimate for the system to calculate an inferred transverse velocity for the pulsar. If the association is real, this inferred velocity should fall within the observed distribution of neutron star velocities (see Arzoumanian et al. 2002).

- **Proper motion.** In some cases, the proper motion of a pulsar can be measured. In a genuine association, the projected proper motion vector should be directed away from the SNR’s centre.

- **Probability of random alignment.** In the absence of other information, a basic indicator as to the likelihood of an association is the probability that the pulsar and the SNR lie near each other on the sky simply by chance. A pulsar sitting just outside a SNR in a complicated region of the inner Galaxy will usually correspond to a spurious association, but a pulsar located at a SNR’s centre in an otherwise empty region of the sky makes for a compelling case.

These criteria cannot all always be applied, and ultimately the judgement as to whether a potential association meets these requirements is a subjective one. If one lesson can be learnt from the claims and counterclaims of associations made over the last few decades, it is that an association is false until proven otherwise! With all this experience in hand, we can turn our attention to AXPs and SGRs, and their potential association with SNRs. However, we quickly find that most of the above criteria cannot be applied to these populations:

- To date, there is no evidence for any interaction of an AXP or SGR with an associated SNR, nor is it even clear whether such an interaction would produce any observable consequences.

- Independent distance estimates to AXPs and SGRs generally come only from measuring the foreground absorption in their X-ray spectra, and are correspondingly highly uncertain. The characteristic age for an AXP or SGR is $\tau_c = P/2\dot{P}$ as for radio pulsars. However, this formula is applicable only if a neutron star’s spin-down is entirely due to steady spin-down resulting from magnetic dipole radiation, while several of the AXPs and SGRs show complicated timing behaviour not consistent with this assumption (e.g. Kaspi et al. 2001a; Woods et al. 2002). Thus there is currently no way to make an independent and accurate distance or age estimate for an AXP/SGR.

- The transverse velocity for an AXP or SGR can be inferred from a potential SNR association, just as for radio pulsars. However, since there are no observational data on the underlying velocity distribution of AXPs and SGRs, there is nothing to which we can compare these inferred velocity estimates.

- Proper motion measurements of AXPs or SGRs would be extremely useful in assessing SNR associations, just as for radio pulsars. However, AXPs and SGRs are generally distant objects, and cannot be observed with VLBI techniques because of their lack of observed radio emission. Thus to date no AXP/SGR proper motions have been measured, nor are there any constraining upper limits.

Thus in considering SNR associations with AXPs and SGRs, all we are usually left with is the probability of random alignment. While this is still a useful criterion, extreme caution must be applied. As an example, in Figure 1 we show the radio emission from $\sim 50$ deg$^2$ of the inner Galaxy, and have marked the positions of the 20 catalogued SNRs and 66 catalogued radio pulsars which fall within this region. If positional coincidence was our only guide, we would conclude that there are about a half dozen pulsar/SNR associations within this region. Application of the above criteria shows that most of these associations are erroneous, and only at most two or three are genuine.
AXPS in SUPERNOVA REMNANTS

Data On AXP/SNR Associations

There are five known AXPs, and a further two AXP candidates (see Mereghetti et al. 2003 for a review). Of these seven sources, three have convincing associations, as discussed by Gaensler et al. (2001) and listed in Table 1. In all three associations, the position of the AXP results in a very low probability of random alignment with the SNR, the age of the SNR is $\lesssim 10$ kyr, and the offset of the AXP from the SNR centre implies a moderate transverse velocity for the neutron star, $\lesssim 500$ km s$^{-1}$.

The environments of the remaining four sources are shown in Figure 2. Of these sources, Gaensler et al. (2001) have shown that RX J170849–400910 is near a possible SNR but is in a very complicated region, that 1E 1048.1–5937 is near the Carina nebula but also has no associated SNR, and that 4U 0142+61 has no nearby sources. More recently, Lamb et al. (2002) have identified an AXP candidate, CXOU J010042.8–721132, in the Small Magellanic Cloud (SMC). As shown in the lower-right panel of Figure 2, CXOU J010042.8–721132 is near the H II region and SNR complex N 66, but again has no specific SNR with which it can be associated.

One might draw the conclusion that the four AXPs without SNR associations are older, or are somehow different, from the three sources embedded in young SNRs. However, a note of caution is that only about half of all young radio pulsars have clear SNR associations. For example, the Crab pulsar, while powering a spectacular synchrotron nebula, has no surrounding SNR representing the ejecta from the associated supernova explosion (e.g. Frail et al. 1995). The lack of SNRs around some young pulsars is usually explained in terms of expansion into a cavity in the ISM or other low density region, and a similar explanation may well apply to the AXPs which lack SNRs.

Implied Properties of AXPs

We have argued above that about half the AXPs (or AXP candidates) can be convincingly associated with SNRs. The associated AXPs all are located at their SNR’s centres, have inferred transverse velocities $\lesssim 500$ km s$^{-1}$, and have ages less than 10 kyr. In all four regards, these properties are very similar to those seen for the youngest radio pulsars and the so-called “central compact objects” (CCOs; see Pavlov et al. 2002). Figure 3 visually demonstrates how all three populations are found to be centrally located in

Table 1. Associations of AXPs and AXP candidates with SNRs.

| AXP             | SNR     | Age (kyr) | Prob of chance align | Implied $V_\perp$ (km s$^{-1}$) | Discovery       |
|-----------------|---------|-----------|----------------------|---------------------------------|----------------|
| 1E 2259+586     | CTB 109 | $\sim 10$ | $5 \times 10^{-4}$   | $< 400$                         | Fahlman and Gregory (1981) |
| 1E 1841–045     | Kes 73  | 2         | $1 \times 10^{-4}$   | $< 500$                         | Vasisht and Gotthelf (1997) |
| AX J1845–0258   | G29.6+0.1 | $< 8$     | $2 \times 10^{-3}$   | $< 500$                         | Gaensler et al. (1999) |

Fig. 1. Pulsars and SNRs in 50 deg$^2$ of the inner Galaxy. The image shows 2.7-GHz radio emission from the survey of Reich et al. (1990). Overlaid are the catalogued SNRs (circles) and pulsars (crosses) in this region of the sky.
Fig. 2. Four AXPs with no obvious SNR association; in each case, the position of the AXP is marked with a “+” symbol. Upper left: 1.4-GHz radio image made using the Very Large Array of the region surrounding RX J170849–400910; the candidate SNR G346.5–0.1 is immediately to the east of the AXP, while the bright SNR G346.6–0.2 is on the eastern edge of the image (Gaensler et al. 2001). Upper right: 0.8-GHz radio image made using the Molonglo Observatory Synthesis Telescope of the region surrounding 1E 1048.1–5937; the Carina Nebula can be seen to the west (Whiteoak 1994). Lower left: 1.4-GHz radio image from the Canadian Galactic Plane Survey of the field containing 4U 0142+61 (Gaensler et al. 2001). Lower right: Hα image of the field around the AXP candidate CXOU J010042.8–721132 in the SMC (Lamb et al. 2002); the H II region / SNR complex N 66 can be seen to the west of the AXP (Ye et al. 1991).
young SNRs, implying that the AXPs are a population of young neutron stars. For radio pulsars, we see many associations in which the SNR is somewhat older and the pulsar is significantly offset from the SNR centre (e.g. Migliazzo et al. 2002). The fact that we do not see such associations for AXPs argues for an observable lifetime for AXPs of $\sim 10$ kyr. We can correspondingly infer a Galactic birth-rate for AXPs of $> 1/2000$ yr (Gaensler et al. 1999).

If the braking torque on AXPs is due to electromagnetic dipole radiation, then a very high magnetic field, $\gtrsim 10^{14}$ G, is needed to slow AXPs from their presumed birth spin periods ($P < 1$ s) to their observed long periods ($P \sim 10$ s) over their short lifetimes. Associations with young SNRs are thus consistent with the magnetar model for AXPs. In order to account for the limited AXP lifetime inferred from these associations, one must invoke a process such as magnetic field decay or rapid surface cooling (Colpi et al. 2000; Duncan 2002), which would render AXPs unobservable at later times.

Some authors have proposed that AXPs are accreting systems (e.g. Mereghetti & Stella 1995). However, such models have problems accounting for the optical/infrared properties of AXPs (Hulleman et al. 2000; Kern & Martin 2002), as well as for their recently discovered X-ray bursts (Gavriil et al. 2002; Kaspi & Gavriil 2002). Unusual accreting scenarios are also required to account for the SNR associations, because of the high braking torque needed to slow the AXPs to long periods over their short lifetimes (e.g. Chatterjee et al. 2000).

For a given age, the size of a SNR in the Sedov phase depends on the kinetic energy of the initial explosion and the density of the ambient medium. Marsden et al. (2001) have taken the SNRs associated with AXPs, estimated a distance to and age for each, adopted a fixed initial explosion energy of $10^{51}$ erg, and have consequently determined the ambient density in each case. These authors find that the densities into which the SNRs containing AXPs are expanding are consistently $\gtrsim 0.1$ cm$^{-3}$, much higher than the density $\sim 0.003$ cm$^{-3}$ typically seen around radio pulsars. Marsden et al. (2001) conclude that a high ambient medium around a supernova explosion is responsible for forming an AXP rather than producing a more normal radio pulsar.

However, there are some important deficiencies in such an argument (see Gaensler et al. 2001 and Duncan 2002 for more detailed discussions). First, the ages and explosion energies of SNRs are typically uncertain by up to a factor of two, while their distances are uncertain to $\sim 20\%$. The resulting estimate of the ambient density is thus uncertain by two orders of magnitude. More fundamentally, there is a serious selection effect inherent in such studies, in that AXPs have mostly been discovered in targeted observations of SNRs, while most radio pulsars are found in all-sky surveys. Since observable SNRs are only produced in dense regions of the interstellar medium (e.g. Kafatos et al. 1980), it is not surprising that the known AXPs are found in such regions also. If one only considers radio pulsars associated with SNRs, one finds ambient densities $\sim 0.2$ cm$^{-3}$ (Frail et al. 1994), no different from that found for AXPs in SNRs by Marsden et al. (2001). Conversely, if one could carry out an all-sky survey for AXPs, one would most likely find that most were in low-density regions. From the available evidence, it thus seems that the environments of the supernovae

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Fig. 3. Images from the *Chandra X-ray Observatory* of the SNRs Kes 73 (left; Slane, private communication), G11.2–0.3 (centre; Kaspi et al. 2000b) and Cas A (right; Tananbaum 1999). These young SNRs are associated with an AXP, a rotation-powered pulsar and a CCO, respectively. In all three cases, the neutron star is located near the SNR's centre.
which produce AXPs are no different from those of the supernovae which produce radio pulsars.

SGRS IN SUPERNOVA REMNANTS

Data On SGR/SNR Associations

There are four known SGRs, plus one SGR candidate (see Hurley 2001 for a review). For all sources, the case for an association with a SNR is considerably less convincing than for the AXP/SNR associations discussed above.

**SGR 0526–66** is on the rim of SNR N49 in the Large Magellanic Cloud (LMC) (Figure 4). This SNR is about 5000 yr old, an age comparable to that seen for the SNRs associated with AXPs. However, an important difference between this potential association and those discussed above is that the neutron star is significantly offset from the SNR centre, implying a transverse space velocity $\sim 1000 \, \text{km} \, \text{s}^{-1}$. Over the whole LMC, the probability of a random alignment between these sources is $\sim 0.002$, but the system lies in a complicated region on the edge of the LMC-4 superbubble, in which several other adjacent SNRs have been identified (Figure 4; Gaensler et al. 2001). Thus while it seems likely that SGR 0526–66 is in a region of recent supernova activity, it is difficult to build a case for a specific association with N49.

**SGR 1806–20** was originally found to be at the centre of the catalogued SNR G10.0–0.3. However, it has since been realised that the SGR is offset by $14''$ from the core of G10.0–0.3 (Kaplan et al. 2000a), while the latter’s amorphous morphology and time-variable behaviour suggests that the classification of G10.0–0.3 is erroneous, it rather being a nebula powered by the luminous blue variable star at its centre (Gaensler et al. 2001). Infrared and millimetre observations have subsequently shown that SGR 1806–20 is associated with a massive star cluster and molecular cloud complex, all at a distance of 15 kpc (e.g. Fuchs et al. 1999).

**SGR 1900+14** is located $\sim 5'$ outside the rim of SNR G42.8+0.6 (see Figure 5). This is a complicated region of the inner Galaxy, and the probability of a random alignment between these two sources is $\sim 4\%$ (Gaensler et al. 2001; Kaplan et al. 2002b). While this alone makes the SGR/SNR association far from compelling, a young ($\tau_c = 38 \, \text{kyr}$) radio pulsar, PSR J1907+0918 immediately adjacent to the SGR could just as likely be associated with the SNR (Lorimer and Xilouris 2000), further increasing the probability that at least one of these two neutron stars is not associated with the SNR. As is the case for SGR 1806–20, SGR 1900+14 is possibly associated with a massive star cluster, at a distance $> 10$ kpc (Vrba et al. 2000).

**SGR 1627–41** is near the SNR G337.0–0.1. The SNR is probably less than 5000 yr old (Sarma et al. 1997), and the SGR’s offset from the SNR correspondingly implies a projected space velocity $>1000 \, \text{km} \, \text{s}^{-1}$ for the SGR. Again, the region is a very complicated one, Figure 6 demonstrating that both the SGR and SNR are embedded in the extended CTB 33 complex, which also contains OH maser emission, molecular...
clouds and several H II regions all at a distance of \( \sim 11 \) kpc (e.g. Corbel et al. 1999). The probability of a random alignment in this case is high, although it is reasonable to suppose that the SGR and SNR are related to the same general episode of star formation and consequent supernova activity.

**SGR 1801–23** is a candidate SGR which has not yet been well-localised, its error box passing near or through several SNRs in a particularly dense region of the Galactic plane (Cline et al. 2000). Until this source is confirmed and its position better refined, it is premature to propose an association of this source with any other object.

### Implied Properties of SGRs

While three out of four of the confirmed SGRs are in the vicinity of SNRs, in all cases the SGR is on the rim of or outside the SNR, implying a transverse velocity \( \gtrsim 1000 \) km s\(^{-1}\). In the absence of any other supporting evidence, none of these associations are very compelling.

However, the fact that SGRs are always near SNRs, as well as possibly being associated with massive star clusters and molecular cloud complexes, makes it clear that SGRs are broadly associated with recent star formation and supernovae. This argues that SGRs are neutron stars with ages \(< 100\) kyr, consistent with their interpretation as magnetars.

Further inferences about the nature of SGRs depend on how one interprets their potential association with SNRs. If one takes the three claimed SGR/SNR associations to be genuine, this implies that SGRs are a high velocity population, distinct from AXPs or radio pulsars. It has been proposed that newborn magnetars might experience asymmetric neutrino recoil (Duncan and Thompson 1992), in which case these anomalously high space velocities are not unexpected. However, this would imply that AXPs and SGRs are separate populations, a conclusion at odds with the many other similarities seen between these two groups of sources (e.g. Kulkarni et al. 2003).

Alternatively, if one concludes that the SGR/SNR associations are spurious, one can interpret the SGRs as a population of neutron stars with ages \(\sim 50\) kyr, whose SNRs have dissipated. The SGRs thus must correspond to an older population than do the AXPs. If the AXPs and SGRs represent evolutionary phases in the life of a magnetar, then this suggests an evolutionary sequence in which AXPs evolve into SGRs (Gaensler et al. 2001). A problem with such a proposal is that it predicts that the spin periods of SGRs should generally be longer than those seen for the AXPs, which is not observed. One possibility is that the AXPs undergo extended periods of spin-up, but such episodes are yet to be seen in long-term monitoring observations (e.g. Gavriil & Kaspi 2002).

A final possibility is that the SGRs and AXPs represent approximately coeval populations of magnetar, but with different progenitor properties. For example, if SGRs result from very massive progenitors, then it is expected that the resulting supernova explosions will always occur in extended low-density wind bubbles. A SNR will be unobservable while expanding into such a bubble, and then would fade rapidly after it collides with swept-up material at the bubble’s edge (Braun et al. 1989). Such a possibility would account for the lack of SNR associations for the SGRs, and would also explain why some of these sources are associated with molecular clouds and massive star clusters.
Recent evidence suggests that AXPs and SGRs are most likely not distinct populations: two AXPs have shown SGR-like bursts (Gavriil et al. 2002; Kaspi & Gavriil 2002), and one SGR has a quiescent spectrum which is very similar to that of an AXP (Kulkarni et al. 2003). However, it is perhaps premature to claim that AXPs and SGRs represent the same underlying group of objects, distinguished only by the manner in which they were discovered. It seems more reasonable to suppose that there is a continuous distribution of properties across the magnetar population: one can speculate that the most massive progenitors result in SGRs, the most highly magnetised neutron stars which are consequently most prone to burst and which are least likely to be associated with SNRs. Lower mass progenitors produce AXPs, which are lower field neutron stars, which burst less often but which are generally associated with SNRs.

CONCLUSIONS

Until a few years ago, there was a great deal of confusion both as to the environmental properties of SGRs and AXPs, and as to what these data were telling us about the nature of these exotic compact objects. However, in the last few years a series of multiwavelength efforts have made the picture more clear.

From these data, we can conclude that some AXPs have convincing SNR associations, which allows us to conclude that AXPs are young (< 10 kyr) neutron stars with relatively low space velocities. On the other hand, the SGRs which have been identified are probably not associated with SNRs, implying that they are either older (≥ 50 kyr) neutron stars whose SNRs have faded, or that they result from massive progenitors in low-density bubbles. The former case is consistent with a scenario in which the AXPs evolve into SGRs, while in the latter case the AXPs and SGRs can be coeval, but might be distinguished by the mass of their progenitor stars.

We are still dealing with a small number of sources, and in several cases the picture is still not completely clear. A number of efforts are being undertaken to clarify these issues. Kaplan et al. are undertaking an extensive multiwavelength project to find new neutron stars in SNRs, Hurley et al. (2001) are measuring the proper motion of SGRs with Chandra to determine whether their implied high space velocities are genuine, and Gaensler et al. are using H I data to search for low density cavities around SGRs. These efforts should provide new clues as to the nature of these intriguing objects.

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