RXTE and "Anomalous" X-ray Pulsars

Victoria M. Kaspi*† and Fotis P. Gavriil*

*Department of Physics, Rutherford Physics Building, McGill University, 3600 University Street, Montreal, Quebec, H3A 2T8, Canada
†Department of Physics and Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139

Abstract. We review the observational properties of the so-called "anomalous X-ray pulsars," a class of young neutron stars having properties very different from most of the population. *RXTE* has provided observations that have made significant progress in our understanding of these sources, which like the "soft gamma repeaters," are today thought to be young, isolated, ultrahigh magnetic field neutron stars, or "magnetars." We briefly discuss the major outstanding questions in this area, and what sort of future X-ray missions would be most likely to allow progress to be made.

INTRODUCTION

Prior to the commissioning of the *Rossi X-ray Timing Observatory* (*RXTE*) in 1996, the so-called "Anomalous" X-ray Pulsars (AXPs) were considered mysterious sources: the energy source for their bright X-ray emission was unknown. At the time, the class consisted of only three members, and was distinguished from other X-ray pulsars by having periods in the narrow range 6–9 s, showing approximately steady spin-down, and having softer spectra. All were known to lie within 1° of the Galactic Plane, and interestingly, one source, 1E 2259+586, was known to reside in a supernova remnant. AXPs as a class were identified as having modest X-ray luminosities, in the range $L_x \sim 10^{34} - 10^{35}$ erg s^{-1}. The leading model to explain the AXPs was that they were accreting neutron stars, although the origin of their difference from other known accreting X-ray pulsars was unclear, and there was no evidence for any companions [1, 2].

The situation in the latter years of *RXTE* is much clearer. The basic phenomenology of the sources is now well mapped out. Here we review the most important observational X-ray properties of the AXP class, which now includes five and possibly eight sources (see Tables 1 and 2). We summarize why today, accretion models are strongly disfavored; rather, the magnetar model, in which AXPs are isolated young neutron stars powered by a decaying ultrahigh magnetic field, provides the most compelling explanation for the unusual AXP source properties, as it does for an equally as exotic class, the soft gamma repeaters (SGRs; see review by Kouveliotou, these proceedings). AXPs have also been reviewed recently by Mereghetti et al. [3] and Kaspi and Gavriil [4].

AXP TIMING PROPERTIES

Since their discovery, AXPs have been known to be spinning down. Unlike most known accreting X-ray pulsars, no evidence was seen for any extended spin-up in nearly two decades of timing. However, some deviations from simple spin-down were reported. 1E 2259+586 showed a handful of possible very short lived spin-up events [e.g. 5] as did 1E 1048−5937 [e.g. 6]. These were noted by various authors and were suggested to be due to accretion torque variations [e.g. 5], glitches [7], and magnetar radiative precession [8]. However, with sparse observations consisting of a frequency measurement every few years and rarely more often, determining the reason for the deviations from simple spin-down was very difficult.

For this reason, a program of regular monitoring of the five confirmed AXPs by *RXTE* was initiated in 1998. The goal was to try to identify the nature of the apparent deviations from simple spin-down, and, if possible, to perform phase-coherent timing, in which every rotation of the neutron star is counted on time scales of months to years. This is effective if the periodicity is very stable, or at least changes relatively slowly. Perhaps surprisingly, this turned out to apply nicely to the AXPs [9]. For example, the RMS phase residual for 1E 2259+586 in ~5 yr of timing (pre-June 2002) is under 2% of the pulse period, following the removal of a model having only three free parameters [10]. Phase-coherent timing on long time scales has now been accomplished for AXPs RXS J1708−4009 [9], 4U 0142+61 [10] and 1E 1841−045 [11] and indicates these sources are capable of great rotational stability. This argues against an accretion origin of the X-rays, since most accreting sources show much higher levels of torque noise [but see

12]. The stability is comparable in some cases (particularly 4U 0142+61 and 1E 2259+586) to that seen in young radio pulsars. Together with the much noisier timing properties of SGRs [e.g. 13], this provides support for a continuum of timing noise properties in the radio pulsar, AXP and SGR populations, in line with the magnetar model. The stability of AXP rotation, at least for 1E 2259+586, seemed at first at odds with the historic record. However, the observed AXP glitches provide a very plausible explanation for the historically observed spin-down deviations for this source. [5].

RXTE observations showed, however, that one AXP, 1E 1048−5937, is a much noisier rotator than the others, so that phase-coherent timing cannot be accomplished over more than a few months [14]. More detailed observations of the source reveal that its spin-down rate can change on time scales of weeks, and by large factors (see Fig. 1; Gavriil & Kaspi, in preparation). This behavior is reminiscent of that seen in SGRs 1806−20 and 1900+14 [15], and is consistent with what was seen in sparser ob-

TABLE 1. Spin parameters for AXPs.

Source	Distance* (kpc)	S NR	P (s)	$\dot{P}$ ($\times 10^{-11}$)	B_{dp} ($\times 10^{14}$ G)	$\dot{E}_s$ ($\times 10^{32}$ erg s^{-1})	τ_c (kyr)	Ref.
4U 0142+61	$\gtrsim 1.0$ or $\gtrsim 2.7$	–	8.69	0.196	1.3	1.2	7.0	1
1E 1048.1–5937	$\gtrsim 2.7$	–	6.45	~ 3.81	~ 5.0	~ 55	~ 2.7	2
1RXS 1708–4009	~ 8	–	11.00	1.86	4.6	5.4	9.4	3
1E 1841–045	5.7-8.5	Kes 73	11.77	4.16	7.1	9.9	4.5	4
1E 2259+586	3	CTB 109	6.98	0.0483	0.59	0.55	230	5
AX J1845.0–0258†	~ 8	Kes 75	6.97	–	–	–	–	6
CXOU J0110043.1–721134†	57	–	8.02	–	–	–	–	7
XTE J1810–197†	~ 10	–	5.54	1.15	2.6	26	7.6	8

* see Özel, Psaltis & Kaspi 2001 for a discussion on distance estimates for the confirmed AXPs; References: (1) Gavriil & Kaspi 2002; (2) Kaspi et al. 2001; (3) Kaspi & Gavriil 2003; (4) Gotthelf et al. 2002; (5) Woods et al. 2003; (6) Torii et al. 1998; (7) Lamb et al. 2003; (8) Ibrahim et al. 2003.

† not confirmed

TABLE 2. Spectral parameters for AXPs.

Source	n_H ($\times 10^{22}$ cm^{-2})	Γ	kT (keV)	L_x (erg s^{-1})	$f_{\rm pl}$ (%) *	Ref.
4U 0142+61	0.88	3.3	0.42	3.3×10^{34}	~ 88	1
1E 1048.1–5937	1.0	2.9	0.63	3.4×10^{34}	~ 80	2
1RXS 1708–4009	1.49	3.1	0.45	6.8×10^{35}	~ 73	3
1E 1841–045	2.0	2.3	–	2.3×10^{35}	100	3
1E 2259+586	0.93	3.6	0.41	1×10^{35}	~ 50	4
AX J1845.0–0258†	9.0	4.6	–	7.4×10^{34}	100	5
CXOU J0110043.1–721134†	0.14	–	0.41	1.5×10^{35}	0	6
XTE J1810–197†	1.05	3.8	0.668	1.6×10^{36}	~ 70	7

* contribution of the power-law component to the total flux, see Perna et al. 2001 for further discussion; References: (1) Juett et al. 2002; (2) Tiengo et al. 2002; (3) Mereghetti et al. 2002; (4) Patel et al 2001; (5) Torii et al. 1998; (6) Lamb et al. 2003; (7) Ibrahim et al. 2003.

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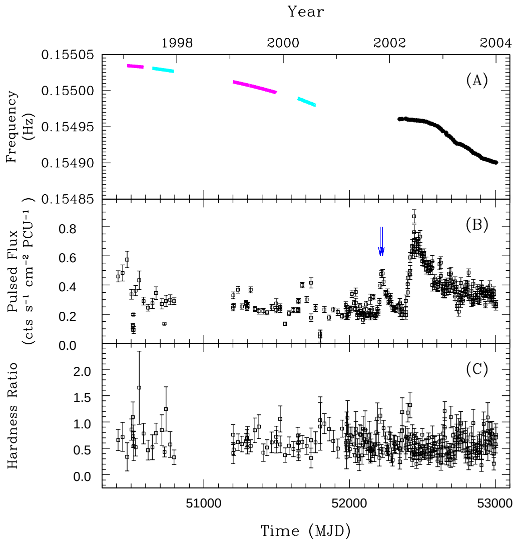

FIGURE 1. (A) Long-term frequency history of 1E 1048−5937 from *RXTE* monitoring [after 14, ; Gavriil & Kaspi, in preparation]. The heavy lines pre-2002 represent intervals over which phase-coherent timing was possible. After 2002, observations began weekly. (B) Pulsed flux in the 2–6 keV band. We have detected clear flux variations in this AXP. The two arrows indicate the epochs of the bursts reported by Gavriil et al. [17]. (C) Hardness ratio computed for the energy range $(2-4\ \text{kev})/(6-10\ \text{keV})$. There are no significant variations in spite of the frequency and pulsed flux variations.

servations previously.

Overall, deviations from simple spin-down in AXPs appears to come in three flavors: (i) glitches and subsequent recovery (see below); (ii) low-level stochastic variations having an apparently "red" spectrum, similar to the "timing noise" seen in radio pulsars; and (iii) large, short-time-scale variations which preclude phase connection. The origin of the latter two in particular is unknown. The low-level variations in radio pulsars may be related to crustal superfluid effects such as "mini-glitches," or may in some cases result from long-term recoveries from past glitches. Arras et al. [16] have recently suggested that the larger-scale torque variations arise from angular momentum transfer from a superfluid core. Such a core, they argue, also results in a reduction in the interior temperature that could make the crust more brittle, hence result in greater burst activity as seen in the SGRs (and possibly 1E 1048−5937; see below).

AXP Glitches

Because phase-coherent timing counts every rotation, it determines spin parameters with high precision. This permits sensitivity to glitches having fractional amplitudes as low as $\sim 10^{-7}$. The first AXP glitch was detected in RXS J1708−4009 [18], and had fractional amplitude 6×10^{-7}, and an increase in the magnitude of the spin-down rate of ∼1%. These glitch properties are similar to those seen in Vela-like radio pulsars. Interestingly, this source glitched again ∼1.5 yr later [19, 20]. However, the second glitch was much larger, with fractional frequency change 4×10^{-6}, and a significant post-glitch recovery in which nearly all of the glitch relaxed on a time scale of ∼50 days. Neither glitch was accompanied by any obvious radiative changes, although the sampling was sparse so brief transient changes could have been missed.

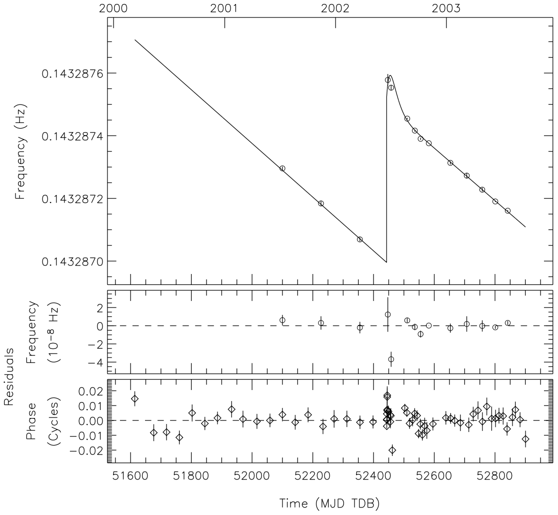

FIGURE 2. Frequency history of 1E 2259+586 around the time of its 2002 outburst based on a phase-coherent analysis. The top plot shows the frequency evolution around the glitch, along with measured frequencies. The middle panel shows frequency residuals, while the bottom shows phase residuals [after 21].

The second discovered AXP glitch was in 1E 2259+586 [22, 21]. It occurred simultaneously with (or possibly a few hours before) a major outburst in which over 80 X-ray bursts were detected in just a few hours (Fig. 3; see below), in addition to sudden order-of-magnitude increases in the pulsed and unpulsed flux, significant pulse profile changes, and an infrared enhancement [22]. This represents the first neutron-star glitch ever observed to be accompanied by significant radiative changes, and clearly indicates a major event that simultaneously affected both the internal and external structure of the star. Roughly 20% of the glitch recovered on a time scale of weeks, and in doing so resulted in the stellar spin-down being a factor of > 2 greater than its pre-outburst value (Fig. 2). This is unprecedented in radio pulsars, and suggests that just following the glitch, the neutron-star superfluid was actually spinning *slower* than the crust, with the observed subsequent enhanced spin-down a result of angular moment transfer from the crust back to the superfluid [after 21].

Glitches are definitely expected in the magnetar model [e.g. 23]. As pointed out by Kaspi et al. [18], at least in principle, an accreting source can undergo a spin-up glitch since the latter results from an internal angular momentum transfer from superfluid to crust regardless of the nature of the external spin-down torque. However, one would not expect simultaneous bursts in an accretion scenario, as one might in the magnetar model. It remains to be seen whether e.g. all large AXP glitches are accompanied by radiative outbursts, and if there is a correlation between glitch amplitude and radiative energy release.

X-RAY BURSTS FROM AXPS

The first discovery of bursts from AXPs came from the *RXTE*/PCA monitoring observations of 1E 1048−5937. Two faint bursts, separated by ∼2 weeks, were detected in ∼425 ks of exposure over ∼5 yr [17]. These bursts very much resemble SGR bursts. Specifically, their fast rise times, short durations, hard spectra relative to the quiescent emission, fluence and probably clustering, are all SGR burst hallmarks. The origin of the bursts could not unambiguously be proven to be the AXP, given the large PCA field-of-view, and the absence of any other radiative or spin change in the source.

Not long after the reporting of the above two bursts, a major outburst consisting of over 80 bursts was detected from the direction of 1E 2259+586 fortuitously during a regular *RXTE*/PCA monitoring observation in 2002 June [22]. The outburst light curve is shown in Figure 3 (top panel). These bursts were very similar to those of SGRs [24]. This is discussed in detail by Gavriil et al., these proceedings. However, one notable difference is that the energy detected in bursts (6×10^{37} erg, 2–60 keV) was much smaller than that in the post-outburst persistent flux enhancement (2×10^{41} erg, 2–10 keV). This could indicate bursting activity that was missed by our observations and the gamma-ray monitors, although the latter would have easily detected SGR-like bursts having the missing energy [21]. This "quiet" outburst strongly suggests there are many more such objects in the Galaxy than was previously thought, as is also indicated by the transient AXP candidates.

AXP X-RAY PULSE PROFILES AND PULSED FRACTIONS

AXP pulse profiles are, like those of the SGRs, broad, with large ($\gtrsim$80%) duty cycles, and generally significant harmonic content [e.g. 10]. The profiles show energy dependences that vary from source to source. A possible trend of greater energy dependence for profiles with higher harmonic content was identified by Gavriil and Kaspi [10], who also showed that in general, AXP pulse profiles are very stable.

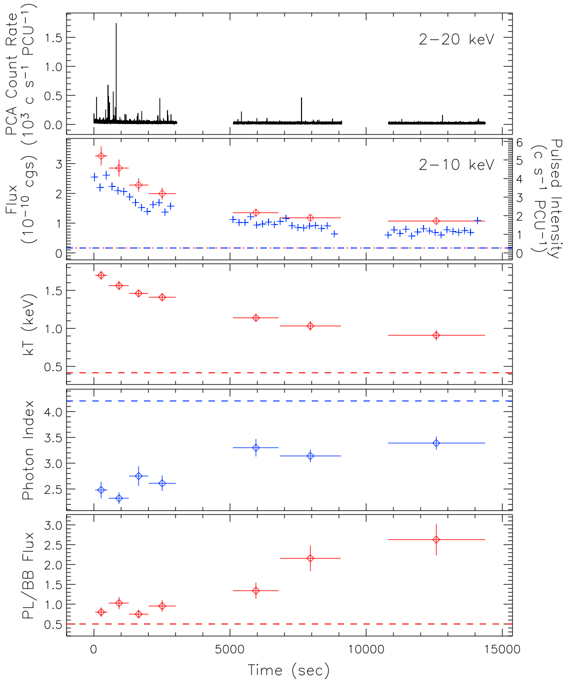

FIGURE 3. Light curve and time evolution of persistent and pulsed emission during the burst observation [22]. Top panel: 2–20 keV *RXTE/PCA* light curve for 1E 2259+586 on June 18, 2002, at 125 ms resolution. The gaps are Earth occultations. 2nd panel: Unabsorbed persistent (diamonds) and pulsed (crosses) fluxes in the 2–10 keV band. The vertical scale of each parameter has the same relative range to show the lower pulsed fraction within this observation relative to the pre-burst value. The horizontal dashed (dotted) lines denote the quiescent (pre-burst) levels of each parameter. 3rd panel: Blackbody temperature of the persistent and pulsed emission spectrum assuming a two-component model consisting of the blackbody and a power law. The same spectral fits show that the blackbody radius remained at ∼1 km throughout. 4th panel: Power-law photon index of the persistent and pulsed emission spectrum for same model as in the 3rd panel. 5th panel: Ratio of the unabsorbed 2–10 keV power-law flux and the bolometric blackbody flux.

However, in 2002 June, simultaneously with the detection of the glitch and X-ray bursts (discussed below), the pulse profile of 1E 2259+586 underwent significant changes, on time scales from hours to days [22, 21]. The profile had relaxed back to its pre-outburst morphology by ∼2 weeks following the outburst. Iwasawa et al. [25]

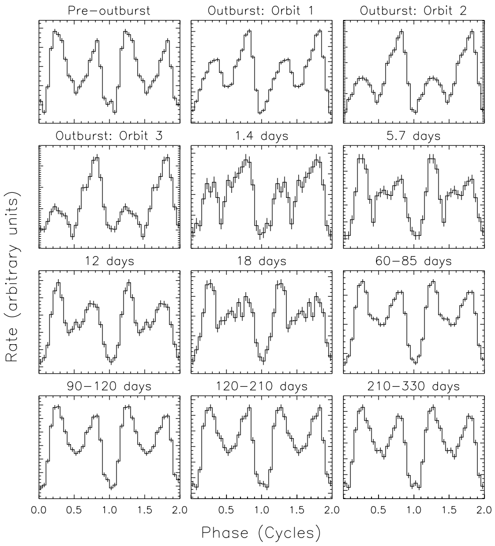

FIGURE 4. Pulse profile changes in 1E 2259+586 seen by *RXTE* around the time of the 2002 June outburst [after 21].

observed an apparent change in the X-ray pulse profile of 1E 2259+586, in which the relative amplitude of the two peaks in the profile changed between observations made in 1989 and 1990. This can be explained as being due to an outburst having occurred just before the 1990 observation (see below).

AXP pulsed fractions vary from source to source, with the highest being ∼0.8 for 1E 1048−5937 and the lowest being ∼0.1 for 4U 0142+61. Some, but not all, are energy dependent, and those which are vary differently with energy. For a summary of AXP pulsed fractions and their energy dependences, see Özel et al. [26].

AXP pulse profiles and pulsed fractions are in principle of considerable interest for constraining models in which AXP emission is observed directly from the stellar surface [e.g. 26, 27]. This is almost certainly an oversimplification; it seems hard to avoid significant magnetospheric effects. In addition, pulsed fractions may be time variable. The pulsed fraction of 1E 2259+586 clearly changed at its 2002 outburst: immediately post-outburst, the pulsed fraction decreased from its quiescent level of ∼0.23 to ∼0.15, however it recovered fully after 3 days [22, 21]

X-RAY SPECTRA

Modeling of X-ray spectra of AXPs generally requires two components, usually taken to be a thermal blackbody component with a power-law tail. The measured spectral parameters of the known AXPs are given in Table 2. The spectra as a class are softer than those of the SGRs in quiescence. The softest source in that class is SGR 0525−66; its spectral parameters are actually softer than those of 1E 1048−5937, which, among other things, prompted Kulkarni et al. [28] and Kaspi et al. [14] to suggest that these sources may be transition objects between the two classes.

In the context of the magnetar model, the spectra can be understood as follows. The thermal component is emerging from the stellar surface, a result of heating of the interior by active magnetic field decay [29, 23]. The thermal spectrum is thought to deviate significantly from that of a blackbody, because of the effects of the stellar atmosphere, as well as the large magnetic field, which results in different opacities for different photon polarizations, as well as on QED vacuum polarization [30, 31, 32, 33, 34]. The thermal spectrum is hardened relative to a blackbody of the same temperature due to the non-grey atmosphere, although vacuum polarization counteracts this slightly. As observers fit the thermal component with a blackbody, some portion of the non-thermal component may result from the atmospheric distortion. However, this portion is probably small. A more promising origin of the non-thermal emission is external resonant Compton scattering of thermal seed photons by magnetospheric currents [35].

Whether AXP spectra are variable is unclear. The pulsed and persistent emission of 1E 2259+586 changed significantly at the time of its 2002 outburst (see Fig. 3). The hardening and subsequent softening of the thermal spectral component in the tail of the flux enhancement seen in 1E 2259+586 is similar to that seen in some SGR bursts [36]. However, the simultaneous flattening and subsequent relaxation of the power-law component in 1E 2259+586 is unprecedented for SGRs. The deviation of the outburst spectrum of 1E 2259+586 from that observed pre-outburst disappeared on a time scale of days, similar to the time scale on which the initial flux enhancement decayed. However, a long-lived "afterglow" remained (see below), even though the spectrum had returned to normal. This argues that AXP spectra are fairly constant in the absence of major events. The stability of the hardness ratios for 1E 1048−5937 (Fig. 1C) in spite of significant torque and pulsed flux variations supports this, although the "snapshot" nature of the PCA monitoring program precludes precision spectral measurements. Even occasional monitoring with an imaging X-ray telescope could clarify things greatly.

AXP X-RAY FLUX VARIABILITY

Strong flux variability pre-*RXTE* was reported for 1E 2259+586 and 1E 1048−5937 [5, 6]. Flux variations of a factor of 5–10 were reported, albeit from different instruments, having different spectral responses, with some imaging and some not. Iwasawa et al. [25] reported a brightening of a factor of ∼2 in a 1990 *GINGA* observation of 1E 2259+586 compared with an observation in 1989. They noted that the 1990 pulse profile was also significantly different than that observed previously, with different relative peak amplitudes, and different peak shapes. Furthermore, the measured 1990 spin period was fractionally shorter by $\sim 3 \times 10^{-6}$ compared with what the previous spin-down rate would have predicted.

In ∼5 yr of monitoring using the PCA on *RXTE*, Gavriil and Kaspi [10] found no evidence for such flux variations in any AXP. This was consistent with what was found by Tiengo et al. [37] in a comparison of past observations of 1E 1048−5937 with recent *XMM-Newton* data. The overall recent lack of variability in AXPs thus appeared worryingly discrepant with the historical record.

The 2002 June outburst of 1E 2259+586 gave a partial solution to this conundrum. Simultaneous with the bursting were increases in the pulsed and persistent fluxes by a factor of > 10 [22, 21], which mostly decayed on a time scale of days, but which has left an X-ray afterglow in which the pulsed flux is still a factor of ∼2 greater than the pre-outburst value a year since the outburst (Fig. 5). The total energy in excess pulsed and persistent emission during the short-decay-time-scale enhancement was 3×10^{39} erg (2–10 keV), while that in the extended afterglow is much more, 2×10^{41} erg [21].

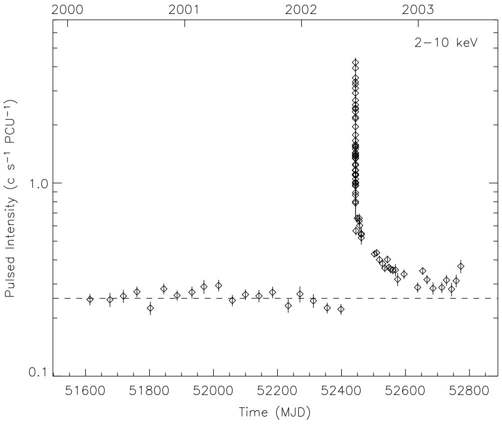

FIGURE 5. The pulsed flux history of 1E 2259+586 (2−10 keV) around the time of the outburst, indicated by the sharp spike [after 21].

As discussed by Woods et al. [21], the rapidly decaying flux enhancement seen in 1E 2259+586 could be due to a transient surface hot spot. During the rapid initial flux decay, the blackbody radius was smaller than at all other times, the temperature was higher, and the pulse profile was clearly different, supporting this picture. Alternatively, it could have been magnetospheric, as a large current density will be excited in the magnetosphere above regions of strong crustal shear. The short-lived afterglows detected after intermediate SGR bursts are explained as the cooling of a pair-rich surface layer heated by a high-energy flare [38]. However, no such flare was seen for 1E 2259+586. This is problematic also for explaining the long-time-scale afterglow. In SGRs, bulk heating of the crust can power an excess heat flux from its surface for a year or more, and has been proposed as the explanation for the quasi-power-law flux decay seen in SGR 1900+14 [39] and SGR 1627−41 [40]. In each case, an initial deposition of 10^{44} erg was assumed, consistent with the detection of an initial giant soft gamma-ray flare; this was unseen for 1E 2259+586. For a more detailed discussion of the possible origins of the enhanced emission, see Woods et al. [21].

Overall, the properties of the outburst in 1E 2259+586 argue that the star suffered a major event that was extended in time and had two components, one tightly localized on the surface of the star (i.e. a fracture or a series of fractures) and the second more broadly distributed (possibly involving a smoother plastic change). The glitch points toward a disturbance within the superfluid interior while the extended flux enhancement and pulse profile change suggest an excitation of magnetospheric currents and crustal heating. The very rich data set provided by this outburst should be very useful in constraining physical properties of the affected neutron star.

The combination of the observed flux enhancement, glitch and pulse profile change in 1E 2259+586 observed by Iwasawa et al. (1992) using *GINGA* are consistent with an outburst similar to that observed in 2002 June having occurred days/weeks prior to their 1990 observation (see earlier on). This offers an estimate of a crude burst rate of two every ∼20 yr.

Very recently we have discovered clear pulsed flux variability in 1E 1048−5937 (Fig. 1B; Gavriil & Kaspi, in preparation). The variation has a possible "fast rise, exponential decay" morphology, similar (though much lower in amplitude) to what was seen for 1E 2259+586. However, for 1E 1048−5937, for the largest observed pulsed flux enhancement, there was no other evidence for bursts, nor for any spectral or pulse profile changes. Interestingly, the two X-ray bursts reported for this source by Gavriil et al. [17] occured near the peak of a smaller pulsed flux enhancement (see Fig. 1B). Whether these flux variations are correlated with torque variations remains to be seen. In any case, these latest *RXTE* data clearly demonstrate that AXPs can have variable pulsed X-ray fluxes in the absence of outbursts.

This observed variability makes the two transient AXP candidates (see Table 1), AX J1845−0258 [41], and XTE J1810−197 [42] easier to understand. These two objects have both shown factor of > 10 increases in their fluxes. For XTE J1810−197, the flux decreased slowly after its appearance, in concert with its spin-down rate, not unlike the behavior seen in 1E 2259+586 post-outburst [42, 21]. Such transient AXPs suggest a large population of quiescent AXPs exists in the Galaxy.

FUTURE MISSIONS

Since the 1996 commissioning of *RXTE*, our overall picture of AXPs has changed dramatically. Perhaps the single most important discovery is that the apparent resemblance of AXPs with SGRs noted by Thompson & Duncan in 1995 is more than skin deep: with the *RXTE* discovery of bursts from AXPs, the two source classes are now united unambiguously. Nevertheless, basic questions about both source classes remain, and have major implications for neutron-star astrophysics in general.

Future X-ray timing missions could play a crucial role in further progress, by addressing two important questions:

- **How many magnetars are there in the Galaxy?** Previously, Kouveliotou et al. [43] suggested the number of active SGRs was $\sim$10, assuming that SGR outbursts would always be detected by wide-field gamma-ray telescopes. The lack of detection of any gamma-ray emission from 1E 2259+586 implies that these objects can have quieter outbursts, making the above number a lower limit only. The detection of "transient" AXPs strongly support this conclusion. How many magnetars could there be in the Galaxy? We can obtain a rough upper limit from the estimated Galactic supernova rate. Cappellaro et al. [44] estimate that one core-collapse supernova occurs every 50–125 yr in our Galaxy. Lyne et al. [45] estimate the birth rate of radio pulsars to be once every 60–330 yr. Although these numbers are roughly similar, they allow for the birth rate of magnetars to be comparable to that of radio pulsars. Assuming this and a magnetar lifetime of 10^4 yr suggests there could be >150 active magnetars of some form in the Galaxy. As some putative AXPs (e.g. AX J1845.0–0258) can have very low luminosities, the most promising way to answer this question is to have a sensitive all-sky monitor looking for faint outbursts from otherwise quiescent magnetars. The upcoming *SWIFT* mission is a first step in this direction, although a wide field X-ray telescope having PCA-like sensitivity would be ideal.
- **What is the structure of a magnetar and how do they work?** Continued monitoring will undoubtedly be important for looking for correlations between timing behavior and radiative properties, as was seen in the 1E 2259+586 outburst and which may be occurring in 1E 1048−5937. Indeed glitches in AXPs may offer a practical method of constraining the structure and physics of these objects. Continued patient timing of these objects has the potential to reveal correlations between glitch properties like amplitude and relaxation time scales with radiative properties, which will help us understand properties of the highly magnetized crust and superfluid interior. For such work, the PCA is actually an excellent instrument, given its sensitivity, time resolution and flexibility in scheduling, although additional sensitivity would always be welcome, particularly for monitoring fainter sources like AX J1845.0–0258.
- **Can we confirm the high B field directly?** X-ray polarimetry has the potential to do this. Owing to the large stellar magnetic field, the atmospheric opacities to radiation having polarization along and perpendicular to the field directions are hugely different. This is predicted to result in high polarization fractions for magnetars, as well as for conventional rotation-powered pulsars. Measuring the polarization of the X-rays from AXPs would not only verify the strength of their magnetic fields but also could provide an estimate of their radius and distance and provide the first demonstration of vacuum birefringence, a predicted but hitherto unobserved quantum electrodynamic (QED) effect [46, 47].

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