J. Astrophys. Astr. (2007) **28,** 185–196

Pulse Phase Dependence of the Magnetar Bursts

Chetana Jain[1,*], Anjan Dutta[1] & Biswajit Paul[2]
[1]*Department of Physics and Astrophysics, University of Delhi, Delhi 110 007, India.*
[2]*Raman Research Institute, Sadashivnagar, C. V. Raman Avenue, Bangalore 560 080, India.*
**e-mail: chetanajain11@yahoo.co.in*

Received 2007 October 3; revised 2008 February 6; accepted 2008 February 8

Abstract. We report here results from a study of X-ray bursts from 3 magnetar candidates (SGR 1806–20, SGR 1900+14 and AXP 1E 2259+586). We have searched for a pulse phase dependence of the X-ray burst rate from these sources. X-ray light curves were obtained with the Proportional Counter Array on-board the Rossi X-ray Timing Explorer during the periods of intense burst activity in these sources. On detailed analysis of the three sources, we found a very significant burst rate for all pulsar phases. However, some locations appear to produce bursts slightly more often, rendering the non-isotropic distribution. Only in the case of SGR 1900+14, there is a clear pulse phase dependence of burst rate.

Key words. Gamma rays: bursts—neutron stars, magnetars: individual (SGR 1806–20, SGR 1900+14 and AXP 1E 2259+586)—X-rays: bursts.

1. Introduction

Soft Gamma-ray Repeaters (SGRs) are a small group of neutron stars with repetitive bursts of soft gamma rays at random intervals. These bursts are of a short duration ~ 0.1 s (Kouveliotou 1995) and have a peak luminosity of $\sim 10^{41}$ erg s^{-1} (Hurley 2000) – well above the standard Eddington limit of $\sim 2 \times 10^{38}$ erg s^{-1} for a 1.4 $M_{\odot}$ neutron star. Other than bursts, these sources show quite stable pulsations though the pulse profiles and pulsed and unpulsed X-ray flux are known to vary with time. Enhancement in pulsed and persistent flux during the burst active phase of the SGRs is believed to result from the back heating of the outer crust by the burst emission in the magnetosphere. Burst repetition timescales have been observed to vary from seconds to years. Three giant flares were observed from SGRs 0526–66 (Mazets *et al.* 1999), 1900+14 (Hurley *et al.* 1999) and 1806–20 (Palmer *et al.* 2005). In SGR 1900+14, the quiescent pulse profile changed from a complex multi-peaked morphology before the August 27, 1998 giant flare to a sinusoidal profile after the burst active episode (Woods *et al.* 2001; Gogus *et al.* 2002). The pulse profile of the SGR 1806–20 became more complex after the December 27, 2004 giant flare (Palmer *et al.* 2005). These X-ray pulsars exhibit a rapid spin down which can be attributed to the magnetic braking of a strongly magnetized neutron star (with magnetic fields $\sim 10^{14}$–10^{15} G), also referred to as 'Magnetars' (Kouveliotou *et al.* 1998). The magnetar theory was proposed (Duncan & Thompson 1992; Thompson & Duncan 1995) to explain the SGR burst activity and the quiescent X-ray emission. These sources have properties similar to another group of neutron stars known as Anomalous X-ray Pulsars (AXPs) which have also been suggested to be magnetars (Thompson & Duncan 1996). The statistical properties of the bursts in SGR 1806–20 (Gogus *et al.* 2000) and SGR 1900+14 (Gogus *et al.* 1999) imply that the SGR bursts resemble earthquakes and solar flares. SGRs have X-ray spectra comparable to that of AXPs when in quiescence. Both AXPs and SGRs have pulse periods ranging from 5–12 s. The pulsed X-ray luminosities of AXPs lie in the range $\sim 10^{33}$–10^{35} erg s^{-1}. It was also proposed (Chatterjee *et al.* 2000; Corbet *et al.* 1995; van Paradijs *et al.* 1995) that they are powered by accretion of fall back material from a supernova. The absence of Doppler shift (or pulse arrival time delay) of the X-ray pulses down to a few millisecond (Mereghetti *et al.* 1998) and the very faint optical counterparts (Hulleman *et al.* 2000a, 2000b; Israel *et al.* 2002) rule out the presence of a binary companion. Most AXPs and SGRs have X-ray spectra that can be modeled by thermal emission of kT ~ 0.5 keV along with a power law tail (Woods *et al.* 1999; Paul *et al.* 2000; Kouveliotou *et al.* 2001). At energies above 10 keV, Kuiper *et al.* (2006), have reported a very hard component in the X-ray spectra of the AXPs. Similar hard spectra have also been detected with INTEGRAL for SGRs (Gotz *et al.* 2006; Mereghetti *et al.* 2005; Molkov *et al.* 2005). However, this very hard X-ray component will not be addressed in this paper.

SGR 1900+14 became extremely active in May, 1998 after a long period of quiescence. A giant flare was recorded on 1998, August 27 (Hurley *et al.* 1999; Feroci *et al.* 2001; Mazets *et al.* 1999). The pulsed flux increased by a factor of ~ 2 above its pre-burst level and the total energy exceeded 10^{44} erg. A total of 200 events were detected with the Burst and Transient Source Experiment (BATSE) on-board the Compton Gamma Ray Observatory (CGRO) during May 1998–January 1999 (Woods *et al.* 1999). PCA on-board RXTE recorded ~ 800 bursts between 1998, May 31 and December 21. After a long quiescence of almost 2 years, a burst was detected on 2001, April 18. The energy released during this intermediate flare was much less than the 1998 flare (Kouveliotou *et al.* 2001). The recurrence time distribution of these bursts is characterized by a log–normal function which peaks at ~ 49 s (Gogus *et al.* 1999). A positive correlation exists between the burst intensity and the waiting times till the next burst. The burst duration and the energy also show a definite relation. Palmer *et al.* (2000) had reported an isotropic distribution of the bursts in SGR 1900+14 using a small fraction of the RXTE observations.

The burst activity of SGR 1806–20 increased during November, 1996 and bursts continued to occur occasionally, unlike the burst activity in SGR 1900+14. SGR 1806–20 entered a phase of increased burst activity in May, 2004 that persisted for ~ 1 year. A giant flare was observed during this period on 2004, December 27 (Hurley *et al.* 2005; Merghetti *et al.* 2005; Palmer *et al.* 2005). This burst had a peak luminosity of $\sim 2 \times 10^{47}$ erg s^{-1}, a total energy of $\sim 5 \times 10^{46}$ erg and a duration of ~ 5 minutes. More than 300 bursts were recorded from the all-sky instruments within the Interplanetary Network (IPN). The SGR 1900+14 bursts are consistent with a power law index of 1.66 while the RXTE bursts of SGR 1806–20 have an index of 1.43. These bursts resemble a self-organized critical system (Bak *et al.* 1998) which if perturbed from the critical state, can cause a chain reaction in the system. SGRs are believed to be strained by the evolving magnetic stresses (Thompson & Duncan 1995). Palmer (1999) reported an isotropic distribution as a function of pulsar phase of bursts in SGR 1806–20 based on 33 bursts detected with the International Cometary Explorer.

AXP 1E 2259+586 is the second AXP after 1E 1048.1–5937 which experienced a major outburst on June 18, 2002. However, very few X-ray bursts were detected from the AXP 1E 1048.1–5937 (Gavriil *et al.* 2002) and therefore the data available from this source are not sufficient for a pulse phase dependence analysis. More than 80 SGR-like bursts were detected from 1E 2259+586 with the RXTE-PCA during a brief observation spanning over 14 ks (Kaspi *et al.* 2003; Woods *et al.* 2004). A significant change in the pulse morphology was observed during and following the outburst. The temporal and statistical properties of these bursts (Gavriil *et al.* 2004) were quite similar to those observed in SGRs. Gavriil *et al.* (2004) claimed detection of a pulse phase dependence of the bursts in 1E 2259+586 with a low statistical significance.

In the present work, we have done a detailed analysis to search for a pulse phase dependence of the bursts from the three magnetar candidates (SGR 1806–20, SGR 1900+14 and AXP 1E 2259+586). The surface of a neutron star may be weaker at some areas which can lead to volcanic sites at these places. In such a scenario, the detection of the bursts is expected to be dependent on the pulse phase.

2. Observations and analysis

We have used archival data from observations of SGR 1806–20, SGR 1900+14 and the magnetar candidate 1E 2259+586 using the Proportional Counter Array (PCA) on-board the Rossi X-ray Timing Explorer (RXTE). The PCA consists of an array of five collimated xenon/methane multi-anode proportional counter units (PCUs) and with a total photon collection area of 6500 cm^2 (Jahoda *et al.* 1996). Data used in the analysis were taken from the event mode and the Good-Xenon-with-Propane mode which records the photon arrival times with 1 μs resolution.

A large number of X-ray bursts were detected from SGR 1806–20 at different times (Gogus *et al.* 2002; Hurley *et al.* 2005; Israel *et al.* 2005; Strohmayer *et al.* 2006). For the present work, we have analyzed data taken from the observations made during 1996, November 5–18 and 2004, May 24 – November 22. During this period, there was a long exposure with RXTE-PCA and the pulse profile was detected with a good signal-to-noise ratio. The 2–10 keV light curve was obtained with a time resolution of 0.03125 s. The total exposure for the 1996 observation was 146.5 ks and for the 2004 observation, the total exposure was 486.6 ks. The source has a variable spin down history. Therefore, from the series of observations in 2004 spread over a period of $\sim$6 months, it was not possible to have a consistent pulse phase connected solution for period evolution for the entire stretch of data. Woods *et al.* (2007) have carried out extensive analysis to obtain the correct spin parameters of SGR 1806–20 during the 2004 observations. We divided the data into small segments of $\sim$10 ks and measured the local spin periods and period derivatives which were found to be consistent with the reported values (Woods *et al.* 2007). For all subsequent analysis of the 2004 dataset, we have used the published pulse ephemerides by Woods *et al.* (2007). To establish the pulse period and the period derivative for the 1996 observation, we carried out pulse folding and χ^2 maximization analysis assuming different trial period derivatives (see Paul *et al.* 2001 for details of the method). The pulse period and the period derivative thus obtained (table 1) was used in further analysis from the 1996 observations.

The source SGR 1900+14 was observed with the RXTE-PCA from August 28 – October 08, 1998 and from April 19 – 30, 2001 during the two active periods of this SGR. The 2–10 keV light curve was created from the PCA data with a time resolution

Table 1. Pulse frequency ephemerides for SGR 1806–20 for the 1996 and 2004 observations, SGR 1900+14 for observations between August 28 and October 08, 1998 and between April 04 and 30, 2001 and for the June 18, 2002 outburst of AXP 1E 2259+586.

Source	Epoch (MJD TDB)	Time range (MJD TDB)	P (s)	$\dot{P}$ (10^{-11} s s^{-1})	Total exposure (ks)
SGR 1806-20	50398	50392–50405	7.4765534	6.8	146.5
SGR 1806-20*	53153	53149–53156	7.5499048	55.8	
SGR 1806-20*	53160	53156–53163	7.5502525	58.7	
SGR 1806-20*	53167	53163–53170	7.5506146	61.0	
SGR 1806-20*	53174	53170–53177	7.5510279	75.2	
SGR 1806-20*	53181	53177–53184	7.5514493	63.8	
SGR 1806-20*	53230	53226–53233	7.5545127	81.0	
SGR 1806-20*	53237	53233–53240	7.5549819	74.2	
SGR 1806-20*	53244	53240–53247	7.5553889	60.5	
SGR 1806-20*	53251	53247–53254	7.5557577	61.0	
SGR 1806-20*	53258	53254–53261	7.5561191	58.2	
SGR 1900+14	51070	50879–51094	5.16026572	5.93	142.2
SGR 1900+14	52021	52019–52030	5.1728219	15.8	106
1E 2259+586	52443	52443–52443	6.9785984	0.047855	10.8

* P and $\dot{P}$: As given in Woods *et al.* (2007).

of 0.03125 s. The total exposure for the 1998 observation was 142.2 ks and for the 2001 observation, it was 106 ks. The pulse ephemeris obtained after the period search and χ^2 maximization is shown in Table 1.

The anomalous X-ray pulsar 1E 2259+586 was observed on 2002, June 18, during which SGR-like bursts were detected for the first time in this source (Kaspi *et al.* 2003). We extracted 2–20 keV band light curve from the PCA data with a time resolution of 0.03125 s. The exposure time for the observation was 10.8 ks. The pulse period and the period derivative was determined from this light curve after the removal of the bursts and are shown in Table 1.

To study the pulse phase dependence of the X-ray bursts in these three sources, estimated background count rates in the same energy band were subtracted from the light curves. The photon arrival times of the background subtracted light curves were converted to the solar system barycenter. To identify the bursts, the counts in the ith time bin were compared with a windowed (one pulse cycle) local running mean spanning about four pulses around the ith time bin (Gavriil *et al.* 2004). A typical burst lasts ~ 0.1 s and a bin size of 0.03125 s was taken for the analysis. Therefore, a window of one pulse period ($\sim$200 bins) around the time bin under consideration is enough to account for the rise and decay of a burst. Hence, the time bins immediately around this point were excluded from contributing to the local running mean. Events for which the count rate was significantly greater than the local running mean were labeled as bursts. The light curves of the three sources were screened and all the bursts (3σ and above) detected using this method were first removed from the light curves. The light curves obtained after the removal of 125 ms of data around these 3σ bursts were folded

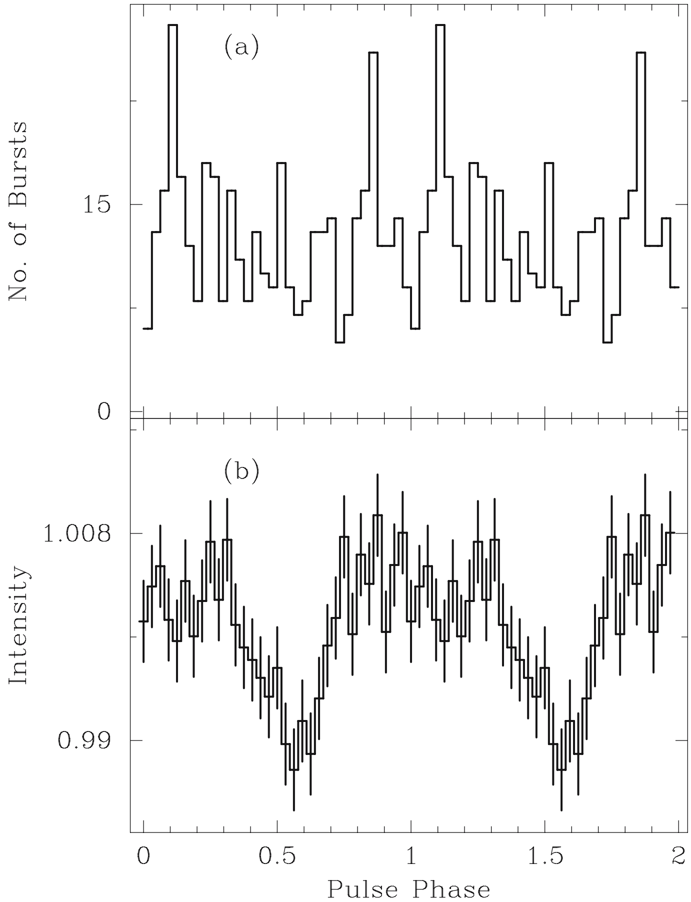

Figure 1. Result of the burst search analysis for the source SGR 1806–20 observed between November 5 and November 18, 1996. The upper panel shows the number of bursts observed for $> 3\sigma$ level of significance. The light curve obtained after the removal of 3σ bursts was folded with 32 phase bins. The bottom panel shows the normalized pulse profile of the source.

with 32 phase bins, along with the parameters listed in Table 1. The folded pulse profiles of all the three sources (SGR 1806–20, SGR 1900+14 and AXP 1E 2259+586) after the removal of all the bursts (3σ and above) are shown in Figs. 1(b), 2(b), 3(b), 4(b) and 5(b). The X-ray profiles of the magnetar candidates varied from a complex multi-peaked morphology to a simple sinusoidal variation. The 2–10 keV pulse profile of the 1996 observation of the SGR 1806–20 is dominated by a broad maximum, while the pulse profile became sinusoidal during the 2004 outburst over the same energy range. The X-ray pulse profile of SGR 1900+14 during the 1998 observation is a single-peaked sinusoidal. The pulse broadened and became more complex during the 2001 outburst. The pulse profile consists of two prominent peaks during the 2002 outburst of the anomalous X-ray pulsar 1E 2259+586. The burst times were converted to the corresponding pulse phase and histograms were made for bursts with detection significance above the 3σ level. This is shown in Figs. 1(a), 2(a), 3(a), 4(a) and 5(a) above the pulse profiles of each observation.

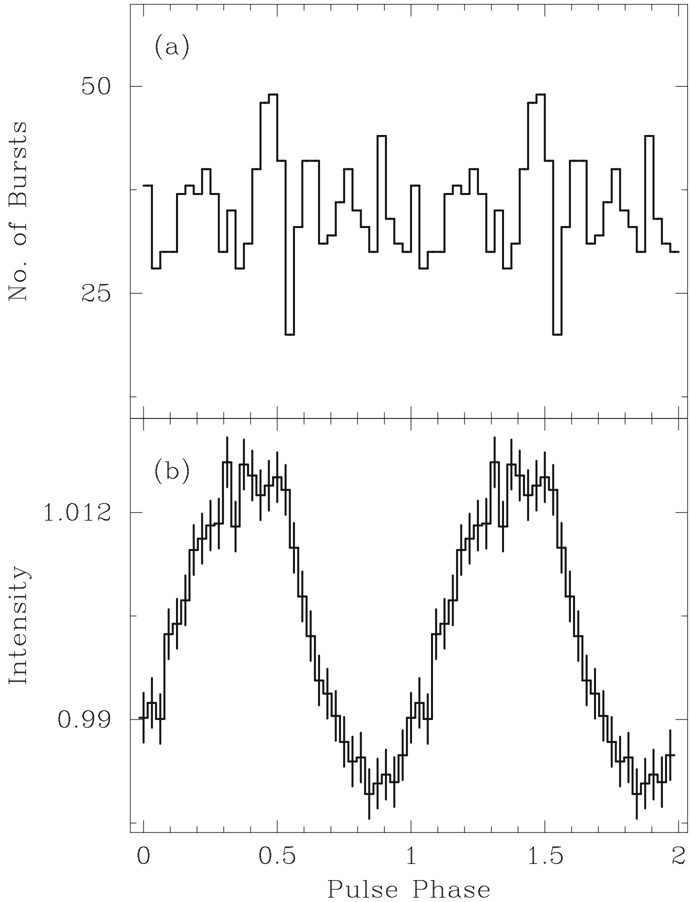

Figure 2. As in Fig. 1, this figure shows the result of the burst search analysis for the source SGR 1806–20 observed between May 24 and November 22, 2004.

As can be seen from Fig. 1, during the 1996 observation of SGR 1806–20 the burst frequency shows two spikes both falling within the peak of the pulse profile. But, fewer bursts were observed during the minimum of the pulse profile. Similarly for the 2004 observation of the same source, a spike is seen in the burst distribution that coincides with the peak of the pulse profile (Fig. 2). For both the observations, the total number of $> 3\sigma$ bursts (N) observed were quite high. During the 1996 observation, a total of 407 $> 3\sigma$ bursts were observed, whereas it was 1128 during the 2004 observations (Table 2). The maximum number of $> 3\sigma$ bursts observed in an interval (N_{max}) were 28 and 49 against an average number (N) of 12.72 and 35.25, respectively for the 1996 and 2004 observations.

From the 1998 observations of SGR 1900+14, shown in Fig. 3, it is evident that the bursts frequency shows a pulse phase dependence with an offset with respect to the pulse profile. The burst frequency at the peak of the distribution is 41 ± 1.3 per bin (calculated from the 14 points near the peak) compared to a value of 29 ± 1.5 (calculated from the 14 points near the minimum), showing a clear pulse phase dependence of the burst rate. There is a clustering of higher and lower burst rates in two phase intervals. In

Table 2. The burst statistics for the magnetar candidates SGR 1806–20 and SGR 1900+14; and the AXP 1E 2259+586.

Source	SGR 1806–20		SGR 1900+14		AXP 1E 2259+586
Year of observation	1996	2004	1998	2001	2002
Total no. of bursts (N)	407	1128	1119	86	87
Max. no. of bursts ($N_{\max}$) in a phase bin	28	49	50	7	8
Av. no. of bursts ($\bar{N}$)	12.72	35.25	34.97	2.69	2.72
Standard deviation (σ_{real})	5.24	6.15	7.40	1.96	2.16
Percentage probability $P(> N_{\max})$ of occurrence of more than $N_{\max}$ bursts in 32 bins*	0.46	52.19	31.05	64.67	22.09
No. of simulated sets (out of 100,000) with $\sigma_{\text{simulated}} > \sigma_{\text{real}}^{**}$	33	35938	2400	7239	1458

*Assuming Poisson distribution, $P(> N_{\max})$ is the probability of occurrence of more than $N_{\max}$ events (in 32 phase bins) about an average number ($\bar{N}$) of random events.
**σ_{real} represents the standard deviation observed in the real dataset, while $\sigma_{\text{simulated}}$ represents the standard deviation observed in the randomly generated datasets.

SGR 1900+14, the bursts are localized but are out of phase with the pulse profile. The detection of a significant burst rate over all pulse phases for both SGR 1806–20 and SGR 1900+14, could imply that the bursts spread over the neutron star surface after the initial outburst (Hurley *et al.* 2002). In the 1998 observations of SGR 1900+14, we observed 1119 bursts (N) spread over the 32 phase bins with an average (N) of 34.97 per interval. A maximum of 50 bursts ($N_{\max}$) were observed in an interval. The 2001 observation of SGR 1900+14 (Fig. 4) suggests a correlation between the burst frequency and the pulse phase. But this is inconclusive due to poor burst statistics.

The burst statistics for the AXP 1E 2259+586 during the 2002 observation (Fig. 5 and Table 2) is also poor. But, it appears that there are two phase intervals with high burst rates (Fig. 5(a)), one coinciding in phase with the first pulse, while the other appears to be leading the second pulse of the profile (Fig. 5b). In this case, a maximum of 8 bursts were observed in an interval.

An analysis was carried out to estimate the deviation of the burst frequency distribution from a constant and detection significance of any peak in the burst distribution. This was carried out independently for the 3σ bursts from each of the observations and the result is shown in Table 2.

For the 1996 and 2004 observations of SGR 1806–20, assuming a Poisson distribution of bursts during the pulse phase, the probability of occurrence of more than $N_{\max}$ bursts (in 32 bins) is about 0.46% and 52.19% respectively. The small probability in the case of the 1996 observation indicates a detection significance of the narrow peak in the burst frequency distribution at the 3σ level. In the case of 1998 observations of SGR 1900+14, the probability of occurrence of 50 or more number of bursts, assuming Poisson statistics, is 31.05%. Further, for the 2001 observation, the probability of occurrence of 7 bursts against an average of 2.69 bursts is 64.67%. A large

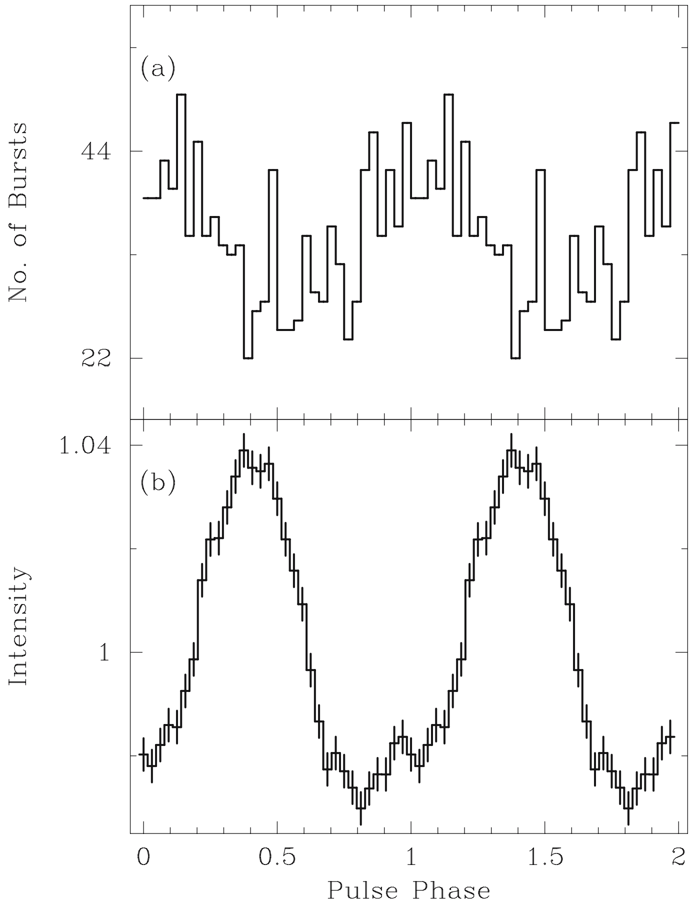

Figure 3. As in Fig. 1, this figure shows the result of the burst search analysis for the source SGR 1900+14 observed between August 28 and October 08, 1998.

probability of occurrence of more than N_{max} bursts, rules out any significant peak in the burst frequency. Hence, nothing definite can be inferred from these observations regarding the presence of narrow peaks in the burst distribution of SGR 1900+14. For AXP 1E 2259+586, the probability of occurrence of more than 8 random events in the 32 bins is 22.09%. Since, this observation has poor statistics, the presence of any peak in the burst frequency cannot be inferred.

Even in the absence of any clear peaks in the burst distribution, the burst frequency can differ from a constant. We have tested the constant frequency hypothesis by generating 100,000 sets of burst distributions for each observation. These sets were simulated using a random number generator by assuming a Poisson distribution about the average number (N) of events. We compared the standard deviation ($\sigma_{simulated}$) of each simulated dataset with the standard deviation (σ_{real}) of the real dataset. In the case of SGR 1806–20, we observed that for the 1996 observations, out of 100,000 simulations, only 33 datasets had a standard deviation greater than the real standard deviation. While it was 35,938 in the case of 2004 observations (Table 2). The results of the two analyses confirm a non-uniform spin phase dependence of the burst distribution during the 1996

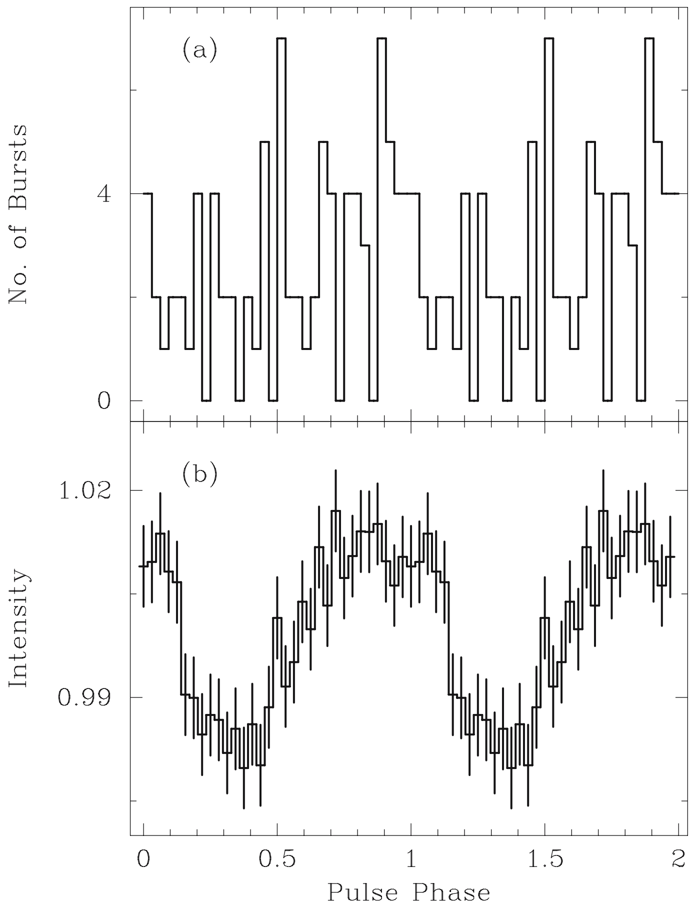

Figure 4. As in Fig. 1, this figure shows the result of the burst search analysis for the source SGR 1900+14 observed between April 19 and April 30, 2001.

observations, however there is no apparent strong clustering in phase. The results from the 2004 observations are inconclusive. Similarly, from the 1998 observations of SGR 1900+14, only 2400 had a standard deviation greater than σ_{real}, which is an indication at the 2.4% level of a non-constant distribution. This is in agreement with the clustering of high and low burst rates reported above. In the case of AXP 1E 2259+586, out of the 100,000 sets, only 1458 had a standard deviation greater than the standard deviation of the real dataset. This also suggests a deviation of the burst frequency from a constant distribution in agreement with indication for the non-uniformity presented above.

3. Discussion

AXP and SGR bursts have many qualitative similarities as has been predicted by the magnetar model. The magnetar model postulates that the short duration SGR bursts are triggered by starquakes induced by magnetic stresses in the neutron star crust (Thompson & Duncan 1996, 2001). The burst active phases vary in both intensity and duration. Burst activity in SGRs is known to be concentrated in time. There is

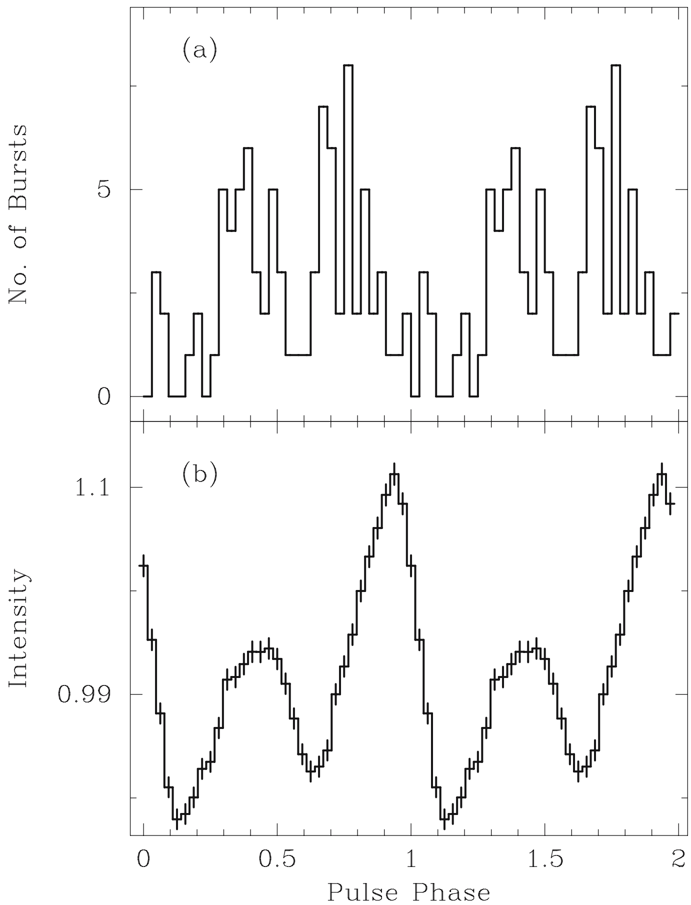

Figure 5. As in Fig. 1, this figure shows the result of the burst search analysis for the magnetar candiate 1E 2259+586 observed on June 18, 2002.

no correlation between the burst energy and the time before the next burst in either the SGRs (Laros *et al.* 1987; Gogus *et al.* 1999), or in 1E 2259+586 (Gavriil *et al.* 2004). But, there is an evidence for a correlation between the burst activity and the time elapsed since the previous burst for SGR 1900+14 (Gogus *et al.* 1999). This suggests that these bursts are not accretion-powered but rather they are triggered by an instability of the stellar magnetic field.

Bursts have been observed to occur for all the pulse phases. In the case of SGR 1806–20, a spike is observed above 3σ significance level when the pulsed intensity is high. Since the spike in the burst distribution is narrow, the phase coincidence with the broad X-ray pulse profile may also happen randomly without any physical significance. Furthermore, in all the three sources, a deviation from a constant burst distribution was observed, ranging in significance from 0.03% in SGR 1806–20, to 2.4% for SGR 1900+14, and 1.5% for AXP 1E 2259+586.

Short and long outbursts of magnetars are believed to arise from injection of energy into the magnetosphere, through a rearrangement of the magnetic field and the formation of dissipation of strong localized currents. The crust provides a site for the initial loss of equilibrium that triggers an outburst (Palmer 1999). The thermal blackbody component of the X-ray emission observed from the magnetar candidates comes from $\sim 1\%$ of the stellar surface (SGR 1900+14: Ibrahim *et al.* 2001; 1E 2259+586: Woods *et al.* 2004). This suggests that the crust develops a network of small dislocations. In view of the results presented here, we propose that the crust of the neutron star has volcanic sites all over the viewed surface. However, few hot spots appear to burst slightly more often. There is a significant detection of a pulse phase dependence, only in the case of SGR 1900+14. For the AXP 1E 2259+586, there is an indication of a possible pulse phase dependence, but the results are inconclusive due to poor statistics. More detailed observations of the magnetars during their active phases, perhaps with the upcoming mission ASTROSAT, will enable us to better understand the bursting behaviour of magnetars.

Acknowledgements

This research has made use of data obtained from the High Energy Astrophysics Science Archive Research Center (HEASARC), provided by NASA's Goddard Space Flight Center. We thank Darshana Ramachandran for help with some preliminary analysis. We also thank the anonymous referee for his valuable advice about the manuscript.

References

Bak, P., Tang, C., Wiessenfeld, K. 1998, *Phys. Rev. A.*, **38**, 364.
Chatterjee, P., Hernquist, L., Narayan, R. 2000, *ApJ*, **534**, 373.
Corbet, R. H. D., Smale, A. P., Qzaki, M., Koyama, K., Iwasawa, K. 1995, *ApJ*, **443**, 786.
Duncan, R. C., Thompson, C. 1992, *ApJ*, **392**, L9.
Feroci, M., Hurley, K., Duncan, R. C., Thompson, C. 2001, *ApJ*, **549**, 1021.
Gavriil, F. P., Kaspi, V. M., Woods, P. M. 2002, *Nature*, **419**, 142.
Gavriil, F. P., Kaspi, V. M., Woods, P. M. 2004, *ApJ*, **607**, 959.
Gogus, E., Woods, P. M., Kouveliotou, C., van Paradijs, J., Briggs, M. S., Duncan, R. C., Thompson, C. 1999, *ApJ*, **526**, L93.
Gogus, E., Woods, P. M., Kouveliotou, C., van Paradijs, J., Briggs, M. S., Duncan, R. C., Thompson, C. 2000, *ApJ*, **532**, L121.
Gogus, E., Kouveliotou, C., Woods, P. M., Finger, M. H., van der Klis, M. 2002, *ApJ*, **577**, 929.
Gotz, D., Mereghetti, S., Tiengo, A., Esposito, P. 2006, *A&A*, **449**, L31.
Hulleman, F., van Kerkwijk, M. H., Verbunt, F. W. M., Kulkarni, S. R. 2000a, *A&A*, **358**, 605.
Hulleman, F., van Kerkwijk, M.H., Kulkarni, S. R. 2000b, *Nature*, **408**, 689.
Hurley, K. *et al.* 1999, *Nature*, **397**, 41.
Hurley, K. 2000, In: AIP Conf. Proc. 526, 5th Hunstville Symp. on Gamma-ray Bursts (eds) Kippen, R. M., Mallozzi, R. S., Fishman, G. F. (New York: AIP), 763.
Hurley, K., Sari, R., Djorgovski, S. G. 2002, astro-ph/11620H.
Hurley, K. *et al.* 2005, *Nature*, **434**, 1098.
Ibrahim, A. I., Strohmayer, T. E., Woods, P. M., Kouveliotou, C., Thompson, C., Duncan, R. C., Dieters, S., Swank, J. H., van Paradijs, J., Finger, M. A. 2001, *ApJ*, **558**, 237.
Israel, G., Mereghetti, S., Stella, L. 2002, *Mem. della Soc. Ast. It.*, **73**, 465.
Israel, G. L., Belloni, T., Stella, L., Rephaeli, Y., Gruber, D. E., Casella, P., Dall'Osso, S., Rea, N., Persic, M., Rothschild, R. E. 2005, *ApJ*, **628**, L53.
Jahoda, K., Swank, J. H., Giles, A. B., Stark, M. J., Strohmayor, T., Zhang, W., Morgan, E. H. 1996, *Proc. SPIE*, **2808**, 59.
Kaspi, V. M., Gavriil, F. P. 2003, *ApJ*, **596**, L71.

Kaspi, V. M., Gavriil, F. P., Woods, P. M., Jensen, J. B., Roberts, M. S. E., Chakrabarty, D. 2003, *ApJ*, **588**, L93.
Kouveliotou, C. 1995, *Ap&SS*, **231**, 49.
Kouveliotou, C. *et al.* 1998, *Nature*, **393**, 235.
Kouveliotou, C., Tennant, A., Woods, P. M., Weisskopf, M. C., Hurley, K., Fender, R. P., Garrington, S. T., Patel, S. K. 2001, *ApJ*, **558**, L47.
Kuiper, L., Hermsen, W., den Hartog, P. R., Collmar, W. 2006, *ApJ*, **645**, 556.
Laros, J. G. *et al.* 1987, *ApJ*, **320**, L111.
Mazets, E. P., Cline, T. L., Aptekar, R. L., Butterworth, P. S., Frederiks, D. D., Golenetskii, S. V., Il'Inskii, V. N., Pal'Shin, V. D. 1999, *Astron. Lett.*, **25**, 635.
Mereghetti, S., Israel, G. L., Stella, L. 1998, *MNRAS*, **296**, 689.
Mereghetti, S., Gotz, D., von Kielin, A., Rau, A., Lichtii, G., Weidensponter, G., Jean, P. 2005, *ApJ*, **624**, L105.
Molkov, S., Hurley, K., Sunyaev, R., Shtykovsky, P., Revnivtsev, M., Kouveliotou, C. 2005, *A&A*, **433**, 13.
Palmer, D. M. 1999, *ApJ*, **512**, L113.
Palmer, D. M. 2000, In: *AIP Conf. Proc. 526, 5th Hunstville Symp. on Gamma-ray Bursts* (eds) Kippen, R. M., Mallozzi, R. S., Fishman, G. F. (New York: AIP), 791.
Palmer, D. M., *et al.* 2005, *Nature*, **434**, 1107.
Paul, B., Kawasaki, M., Dotani, T., Nagase, F. 2000, *ApJ*, **537**, 319.
Paul, B., Agrawal, P. C., Mukerjee, K., Rao, A. R., Seetha, S., Kasturirangan, K. 2001, *A&A*, **370**, 529.
Strohmayer, T. E., Watts, A. L. 2006, *ApJ*, **653**, 593.
Thompson, C., Duncan, R. C. 1995, *MNRAS*, **275**, 255.
Thompson, C., Duncan, R. C. 1996, *ApJ*, **473**, 322.
Thompson, C., Duncan, R. C. 2001, *ApJ*, **561**, 980.
van Paradijs, J., Taam, R. E., van den Heuvel, E. P. J. 1995, *A&A*, **299**, L41.
Woods, P. M., Kouveliotou, C., van Paradijs, J., Finger, M. H., Thompson, C., Duncan, R. C., Hurley, K., Strohmayer, T., Swank, J., Murakami, T. 1999, *ApJ*, **524**, L55.
Woods, P. M., Kouveliotou, C., Gogus, E., Finger, M. H., Swank, J., Smith, D. A., Hurley, K., Thompson, C. 2001, *ApJ*, **552**, 748.
Woods, P. M., Kaspi, V. M., Thompson, C., Gavriil, F. P., Marshall, H. L., Chakrabarty, D., Flanagan, K., Heyl, J., Hernquist, L. 2004, *ApJ*, **605**, 378.
Woods, P. M., Kouveliotou, C., Finger, M. H., Gogus, E., Wilson, C. A., Patel, S. K., Hurley, K., Swank J. H. 2007, *ApJ*, **654**, 470.