A Comprehensive Study of Pulse Profile Evolution in SGR 1806-20 & SGR 1900+14 with the RXTE PCA

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ABSTRACT

Soft Gamma Repeaters undergo pulse profile changes in connection with their burst activity. Here we present a comprehensive pulse profile history of SGR 1806-20 and SGR 1900+14 in three energy bands using Rossi X-ray Timing Explorer/Proportional Counter Array observations performed between 1996 and 2001. Using the Fourier harmonic powers of pulse profiles, we quantify the pulse shape evolution. Moreover, we determined the RMS pulsed count rates (PCRs) of each profile. We show that the pulse profiles of SGR 1806–20 remain single pulsed showing only modest changes for most of our observing span, while those of SGR 1900+14 change remarkably in all energy bands. Highly significant pulsations from SGR 1900+14 following the 1998 August 27 and 2001 April 18 bursts enabled us to study not only the decay of PCRs in different energy bands but also their correlations with each other.

Subject headings: stars: individual (SGR 1806-20) – stars: individual (SGR 1900+14)

1. Introduction

Soft gamma repeaters (SGR) constitute a small class of isolated neutron stars; four are currently well-established while one more source remains an unconfirmed candidate (Cline

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et al. 2000). As their name indicates, SGR emission is repetitive: during their active states each source emits hundreds of short (duration \( \sim 0.1 \) s), intense (at \( \sim \) super-Eddington luminosities) bursts of hard X-rays / soft gamma-rays at random intervals. Very rarely, (observed once so far from each of SGR 0526−66 and 1900+14) they emit a giant flare, an event with \( \sim 10^4 \) higher luminosity than the typical short events (Mazets et al. 1979, Hurley et al. 1999a, Feroci, et al. 2001). Thompson & Duncan (1995; henceforth TD95) proposed that the SGR burst activity is associated with the strong magnetic field \( (B \gtrsim 10^{14} \text{ G}) \) of the neutron star. Their model, also known as the magnetar model, attributes SGR bursts to various levels of fracturing of the neutron star crust by the motion of the anchored lines of their strong magnetic fields (TD95, Thompson & Duncan 2001).

SGR sources were established as a new class in the mid 80s based on their bursting properties. The first X-ray counterpart of an SGR was discovered in 1993 with the Japanese satellite ASCA (Murakami et al. 1994) after SGR 1806−20 triggered the Burst And Transient Source Experiment (BATSE) onboard the Compton Gamma Ray Observatory (CGRO) (Kouveliotou et al. 1994). All four SGRs are currently associated with persistent X-ray point sources with luminosities \( 10^{34} \sim 10^{35} \text{ ergs s}^{-1} \). Their energy spectra are nominally fit with a single power law with photon indices \( 2 \sim 3.2 \), except in the case of SGR 1900+14, where a two component spectrum (blackbody of \( kT \approx 0.50(4) \) and power law with index \( = 2.1(3) \)) has been established with BeppoSAX and Chandra observations (Woods et al. 1999a, Kouveliotou et al. 2001).

Observations of SGR 1806−20 with the Rossi X-Ray Timing Explorer (RXTE) Proportional Counter Array (PCA) on November 1996 led to the discovery of the first SGR spin period of 7.47 s. Further RXTE/PCA observations established that the source exhibited a very rapid spin-down rate of \( 8.1 \times 10^{-11} \text{ s s}^{-1} \), providing the first direct measurement of the neutron star magnetic field of \( \sim 2 \times 10^{14} \text{ G} \), in agreement with the magnetar model of TD95 (Kouveliotou et al. 1998a). ASCA observations of SGR 1900+14 in 1998 led to the discovery of a spin period for that source (Hurley et al. 1999b) and to the detection of its rapid \( (1.1 \times 10^{-10} \text{ s s}^{-1}) \) spin down rate (Kouveliotou et al. 1999). Of the two remaining SGRs, SGR 0526−66 has been associated with an 8 s spin period, originally seen as intensity modulation in the decaying tail of the giant flare it emitted in 5 March 1979 (Mazets et al. 1979). A pair of recent Chandra observations of this source during quiescence spaced \( \sim 1 \) year apart should establish the periodicity and spin down rate of SGR 0526−66 (Kulkarni et al. 2002). The last source, SGR 1627−41, is the dimmest of them all and no spin modulation has been detected in its persistent X-ray flux (Kouveliotou et al. 1998b).

\(^6\)Assuming that the star slows down via magnetic dipole radiation, \( B_d \propto \sqrt{PP} \).
In 1998 we started a monitoring campaign with RXTE/PCA for the two SGR sources with clearly established spin and spin down rates. Our observations so far have shown that these spin down rates vary significantly, sometimes by a factor of four, and that they exhibit a very high level of timing noise (Woods et al. 2000, 2002). Earlier results have also indicated a relationship between the pulse profile complexity and the activity history of the source (Woods et al. 2001). In this paper we construct the first detailed history of the pulse profile evolution of SGR 1806 − 20 and SGR 1900 + 14 spanning the last ∼ 5 years, and we examine their evolution with energy. We quantify the profile changes by estimating the power in their respective Fourier harmonics. In Section 2, we describe our observations and how we deal with the X-ray background component in our data. In Section 3, we describe the methodology of our data analysis and present the results; we discuss the implications of our results in Section 4.

2. Observations

The RXTE/PCA has 5 identical Proportional Counter Units (PCUs) with a total effective area of ∼ 6500 cm², a field of view of ∼ 1° FWHM, and is sensitive to photon energies between 2 − 60 keV. Also onboard RXTE, the High Energy X-ray Timing Experiment (HEXTE) consists of two clusters of NaI/CSI scintillation detectors sensitive to photon energies of 15 − 250 keV. Although we searched the HEXTE data, we have not detected any pulsations at the SGR frequencies; therefore, here we present only results obtained with the RXTE/PCA.

During our ongoing monitoring campaign and also during occasional target of opportunity observations when burst activity was detected, we have observed SGR 1806 − 20 and SGR 1900 + 14 with RXTE over 2 Ms. In Table 1 we list the observation epochs, their date ranges, number of observation and total (on source) exposure times of each epoch for SGR 1806 − 20. Similarly, in Table 2 we list those for SGR 1900 + 14 with an extra column where we report the occasional presence of 4U 1907 + 07 and XTE J1906 + 09 in the PCA field of view.

For each observation we used the `sextract` utility of FTOOLS 5.0, to generate the source intensity light curves from the event mode PCA data with 0.125 s time resolution in 3 energy bands: 2 − 5 keV, 5 − 10 keV and 10 − 20 keV. We filtered out the times of data anomalies, such as times of large pointing offsets and times of SGR burst activity, using the appropriate housekeeping data to obtain the persistent SGR emission plus the background. As the PCA is currently operating with varying number of PCUs, we normalized the rates of each time bin to the number of active PCUs. Finally we corrected the photon arrival times to the solar
system barycenter using \textit{fxbary} for observations prior to 2000 December 31 and \textit{faxbary} for the later ones.

2.1. Background Issues

Estimating the X-ray background emission with the PCA is not a trivial problem. We had to account for various background components included in the observed emission simply due to the relatively large field of view of the PCA. Since both SGRs are located in the galactic ridge region, there are also inevitably other sources occasionally active in the same field. During the vast majority of these observations the count rates of both SGRs were very low in comparison to the total (source + background) count rate; namely in 1996 epoch of SGR 1806−20 the average total rates in $2 - 5$ keV, $5 - 10$ keV and $10 - 20$ keV bands were 44.32, 51.76 and 47.36 counts s$^{-1}$ PCU$^{-1}$, respectively, while the expected source count rates (estimated by employing WebPIMMS with an interstellar medium attenuated [$N_H = 6.1 \times 10^{22}$ cm$^{-2}$] power law model [$\Gamma = 1.97$], Mereghetti et al. [2000]) were 0.35, 0.57 and 0.31 counts s$^{-1}$ PCU$^{-1}$, respectively. Similarly the average observed count rates for SGR 1900+14 were 39.36, 49.52 and 50.32 counts s$^{-1}$ PCU$^{-1}$ in three energy bands, whereas the expected source rates were only 0.27, 0.35 and 0.19 counts s$^{-1}$ PCU$^{-1}$ (using the spectral model of a blackbody [$kT_{BB}=0.5$ keV] plus a power law [$\Gamma = 2.1$], both attenuated by the interstellar absorption [$N_H = 2.3 \times 10^{22}$ cm$^{-2}$], Kouveliotou et al. [2001]). Below we describe the different components that contribute to the background of each source and our efforts to determine their values. Nonetheless, we are unable to estimate the background level with enough accuracy to determine the source count rates.

\textit{(i) Instrumental Background:} This is due to events created by the particles in the vicinity of the instrument. For each observation, we have created a PCA background event data file using the faint background models (provided by the PCA instrument team for each epoch). We then extracted the background light curves in all 3 energy intervals and processed them as described in Section 2. We then determined the average background rate per PCU per epoch.

\textit{(ii) Galactic Ridge Contribution:} There have been numerous attempts to model the diffuse emission of this region. The most recent and extensive one is by Valinia & Marshall (1998) using RXTE measurements. We reproduced the diffuse galactic ridge spectrum by employing their estimated parameters of a two-component thermal plasma plus power law model for their R1 region (within which both SGRs are located) and the PCA response matrix (with all 5 PCUs operating). We then estimated the count rates (per PCU) in each of our energy bands for each epoch.
There are two known point X-ray sources in the vicinity of SGR 1900 + 14: 4U 1907 + 09 (a persistent X-ray pulsar with spin period of $\sim 440$ s, located 0.51° away from the SGR) and XTE J1906 + 09 (a transient X-ray pulsar with 89 s spin period at 0.28° away). For the former source, we have used the average spectral model parameters and flux given by Roberts et al. (2001) to estimate its count rate. We then used the PCA collimator response at the pointing offset to this source during each observation to estimate the rates from 4U 1907 + 09 that would be present during our observations. For the latter source, Wilson et al. (2002) have performed an extensive search for periods of outburst activity, using the same data set presented here up until the end of 2000. They determined two active episodes, one each in 1996 and 1998. We then determined the expected rates from XTE J1906 + 09 by using their best model parameter estimates for each of the outburst periods, following the same procedure as for the former source.

After subtracting the background contribution estimated by taking account all the above described components, we constructed the 2 – 5 keV and 5 – 10 keV pulse profiles for each source. We then compared our results with those obtained (within the same energy bands) from contemporaneous measurements with imaging instruments (BeppoSAX/NFI observations of SGR 1900 + 14 in September 1998 and Chandra/ACIS–S observations of SGR 1806 − 20 in August 2000). Even though the pulse profiles resembled each other significantly, the RMS pulse fractions obtained with the PCA measurements were smaller than those of BeppoSAX or Chandra by a factor of $\sim 3$. (Here we define the pulse fraction as $PF_{RMS} = \sqrt{\sum_{i=1}^{N}[R_i - R_{ave}]^2/R_{\text{min}}^2/N}$, where R represents the count rate in each phase bin). These results indicate that there is still a significant background contribution in our data, or alternatively, that despite all our efforts we still severely underestimate our background. Although we cannot accurately determine our source of error, we believe that it is mostly due to underestimating the galactic ridge background contribution. We will refrain, therefore, in the following from calculating pulse fractions or hardness ratios (ratios of different energy fluences) that are based on background-subtracted data and will use the background-independent method described in Section 3 to draw physical conclusions on the pulse profile properties.

3. Pulse Profiles

In several of our observations the sources were offset from the center of the PCA field of view to either reduce the likelihood of saturation from bursts (when they were very active) or to reduce occasional contributions from other transients. We have taken these pointing offsets into account by applying the appropriate collimator response corrections for all datasets. We
then created pulse profile histories in three energy bands (2 − 5, 5 − 10 and 10 − 20 keV) for each source using phase-connected pulse ephemerides reported elsewhere (Woods et al. 1999b, 2000, 2002).

We quantify the pulse profile shapes (and changes) with the powers of their Fourier harmonics: for each source, we Fourier transformed each profile and calculated the normalized Fourier Powers (FP) of the first 5 harmonics as follows. We first estimated the powers as $P_k = 2(a_k^2 + b_k^2)/(\sigma_{a_k}^2 + \sigma_{b_k}^2)$, where $a_k$ and $b_k$ are the coefficients of the sine and cosine terms of the Fourier series, respectively, and $\sigma_{a_k}$ and $\sigma_{b_k}$ are the standard deviations of these coefficients. This is equivalent to the Leahy normalization standardly used in X-ray astronomy. Using the formalism described by Groth (1975) with the estimated power values, we measured the median and 68 % significance level of the Groth distribution. We then corrected the estimated powers for the binning of the pulse profile, which is a prominent effect on the powers of higher harmonics, using equation 2.19 of van der Klis (1989). The resulting powers of each profile were then normalized by the total power.

We have applied the following procedure to obtain a quantitative measure of the level of pulsed intensity of the source during each observation. We estimated the average count rate, $R_{ave}$, of each profile and then calculated the rms pulsed count rate, $PCR_{rms}$, per source as $PCR_{rms} = \sqrt{\sum_{i=1}^{N}(R_i - R_{ave})^2 - (\Delta R_i)^2}/N$, where $R_i$ is the count rate in each phase bin, $\Delta R_i$ are the associated Poisson statistical errors and $N$ is the number of phase bins (which is 20). Typically, $\sum_{i=1}^{N}(\Delta R_i)^2$ is about 23, 9 and 37 % of $\sum_{i=1}^{N}(R_i - R_{ave})^2$ for the 2 − 5, 5 − 10 and 10 − 20 keV pulse profiles of SGR 1806 − 20. Note that the above percentage can be as high as 81 % if the pulsation is very weak. The rms value of the pulsed count rate is a background-immune measure and provides a reliable indicator of the pulsed intensity.

3.1. SGR 1806 − 20

We exhibit in the three upper panels of Figure 1 the pulse profile changes over time and energy of the source. Note that the rates in the profiles are in arbitrary units on account of the background contamination as explained in Section 2. The bottom panel displays the quantitative evolution of the harmonic contents in its Fourier spectrum. At all epochs, we find that most of the power is in the first harmonic of the Fourier spectrum.

As reported in Woods et al. (2002), observations between 2000 July 4 to September 3 could not be phase connected. For these data we employed a phase-aligning technique to obtain the overall pulse shape. We first created a template pulse profile using 55 days of a phase-connected timing solution (data between 2000 May 2 and June 25). We then folded
Fig. 1.— (upper 3 panels) Pulse profiles of SGR 1806-20 as observed in 1996, 1999, 2000 and 2001 (from left to right) in 2–5 keV, 5–10 keV and 10–20 keV energy bands. The count rates are in arbitrary units as explained in the text; (bottom panel) Normalized power of the pulse profile Fourier harmonics vs associated harmonic number for each profile. The error bars associated with the 2–5 keV and 5–10 keV values are shifted to the left and right, respectively, for displaying purposes.
each of our non-phase connected data sets at the spin frequency measured for these data sets
(Table 3 in Woods et al. 2002). Next, we determined the phase offset of each profile with
respect to this template by fitting the first four Fourier coefficients of the folded profile to
the same coefficients of the template as described in Finger et al. (1999). Then, finally we
aligned the profiles, and obtained the average pulse shape for the 2000 epoch of the source.
The relative alignment errors were small (less than 5%) so that this process should not
introduce any significant smearing of the pulse profile.

The pulse harmonic content before and during the 1996 source activation is distributed
into two harmonics. We investigated the evolution of the pulse profile during our two week
long RXTE observations in 1996 (which is the last period where we observe a complex
profile) by subdividing our data into three sets of ~45 ks each. We find that all profiles
are consistent with each other, showing no major changes in complexity. In 1999 and 2000,
the pulse profiles are significantly sinusoidal and resume a marginally more complex shape
during late 2001. As the source was barely active during this latter period, however, the
pulsed signal is weaker and almost undetectable above 10 keV. In general, the pulse profiles
are relatively wide, covering ~80% of the phase cycle, except in the 1999 observations where
it becomes narrower covering ~50% of the cycle.

To investigate the dependence of the pulse shape on the source activity we plot in the
upper panel of Figure 2 the source burst activity (grey histogram) detected with BATSE
covering the period of our RXTE monitoring program until the reentry of CGRO on June
2000. The data points in the plot are the values of the normalized Fourier power in the first
harmonic only (in three energy bands). The power increases during 1999 and reduces down
to the 1996 level in 2001. The bottom panel in Figure 2 exhibits the rms pulsed count rate
of the source in each energy range overplotted on the cumulative energy distribution of all
bursts from the source detected with BATSE since 1996. We note that the count rate (and
thereby the source pulsed flux intensity) remains fairly constant during our observations and
that the pulsed rates between 5 – 10 keV are always larger than those in each remaining
energy band. There is no measurable variability in the rms pulsed count rate with burst
activity. There is, however, intense burst activity between our pulse shape measurements in
1996 and 1999 which may be the cause for this pulse shape change (see also §4).

3.2. SGR 1900 + 14

We have performed a similar analysis for SGR 1900 + 14. Figures 3 through 5 exhibit
the pulse shape and its harmonic content evolution over a series of quiescent and active
episodes of the source.
Fig. 2.— *(upper panel)* History of the power in the fundamental (3 energy bands) for SGR 1806-20 along with the burst activity history of this source as seen with BATSE. The horizontal bars at the Fourier power points denote the time spans of each observing cycle. The dotted region starts after the reentry of CGRO. *(bottom panel)* The history of the rms pulsed count rate in each energy range during the same period. The solid line is the cumulative normalized burst fluences detected with BATSE.
In 1996, the source was in quiescence with no burst activity detected. A three-peak pulse profile is seen in all three energy bands, with all peaks aligning in phase (Figure 3, left column). As we can also see in the FPs plot, the majority of power is in the third harmonic of each profile. The distinct, rapid, large modulation in the 10\textendash20 keV has not been seen with similar significance in any other epoch. Even though the source entered a burst active episode in the end of May 1998 (emitting numerous, short SGR bursts), the shape of its pulse profile resembles the one of the 1996 observations (Figure 3, middle column).

On 27 August 1998, however, SGR 1900 + 14 emitted a 'giant flare' as described in the Introduction. In the tail emission of this burst, which was strongly modulated at the spin period of the neutron star, Feroci et al. (2001) observed a highly significant four-peaked pulse profile (between t+40 s and t+90 s, where t is the trigger time of flare); the profile became almost sinusoidal at \( \sim t+300 \) s. Our August 1998 pulse profile here covers four days starting the day after the burst. The pulse profile is also simplified to a broad main pulse plus a secondary peak (or shoulder) at \( \phi \sim 0.8 \) (Figure 3, right column). The main pulse covers almost half the spin cycle.

Over the next 2 months after the giant event, the 2\textendash5 keV band pulse profile remained almost identical to that of the very short epoch soon after the flare (Figure 4, left column). In the 5\textendash10 keV profile, the main pulse structure did not change but there is some evidence that the secondary peak feature appears earlier in phase than in the 2\textendash5 keV profile. The secondary peak structure is more significant between 10 \textendash 20 keV during this epoch. The main pulses in 10\textendash20 keV during both August 1998 and September-October 1998 cover a slightly shorter phase (compared to the lower energy bands) and display sharp rise and fall times.

SGR 1900 + 14 observations between 1999 January 25 and July 27 could not be phase connected (Woods et al. 2002). Similar to SGR 1806 \textendash 20, we used the pulse profile of a 14 day segment of phase connected data early in January 1999 as our template. With this template and using individual pulse frequency measurements for non-phase connected observations as given by Woods et al. (2002) we employed the same phase-aligning procedure to get the average pulse profile of SGR 1900 + 14 in 1999 (Figure 4, middle column). The 2\textendash5 keV and 5\textendash10 keV profiles are described by a broad single pulse covering almost 75\% of the phase cycle; there is no evidence of a secondary peak in the FP in all bands.

In 2000, the pulse profiles in the 2\textendash5 keV and 5\textendash10 keV bands are dominated by a single pulse with \( \sim 75\% \) of phase coverage (Figure 4, right panel). Both profiles show a sharp rise followed by a gradual fall. The high power in the second harmonic of the 2\textendash5 keV band is due to the emission enhancement around \( \phi \sim 0.6 \). In this epoch, only weak pulsations were seen in the 10\textendash20 keV energy band.
Fig. 3.— (upper 3 panels) Pulse profiles of SGR 1900+14 as observed in 1996, May 1998, and August 1998 (from left to right) in 2–5 keV, 5–10 keV and 10–20 keV energy bands. The count rates are in arbitrary units as explained in the text; (bottom panel) Normalized power of the pulse profile Fourier harmonics vs associated harmonic number for each profile. The error bars associated with the 2–5 keV and 5–10 keV values are shifted to the left and right, respectively, for displaying purposes.
Fig. 4.— (upper 3 panels) Pulse profiles of SGR 1900+14 as observed in September-October 1998, 1999 and 2000 (from left to right) in 2–5 keV, 5–10 keV and 10–20 keV energy bands. The count rates are in arbitrary units as explained in the text; (bottom panel) Normalized power of the pulse profile Fourier harmonics vs associated harmonic number for each profile. The error bars associated with the 2–5 keV and 5–10 keV values are shifted to the left and right, respectively, for displaying purposes.
Fig. 5.— (upper 3 panels) Pulse profiles of SGR 1900+14 as observed on 14 April 2001, April-May 2001 and June-July 2001 (from left to right) in 2–5 keV, 5–10 keV and 10–20 keV energy bands. The count rates are in arbitrary units as explained in the text; (bottom panel) Normalized power of the pulse profile Fourier harmonics vs associated harmonic number for each profile. The error bars associated with the 2–5 keV and 5–10 keV values are shifted to the left and right, respectively, for displaying purposes.
Our ongoing SGR monitoring campaign with RXTE revealed that SGR 1900+14 was in quiescence at least over the last 8 months in 1999 and throughout 2000. The source entered a new episode of burst activity starting with an intermediate intensity SGR flare detected on 18 April 2001 (Guidorzi et al. 2001). This event resembled the August 27 giant flare in some respects but was weaker energetically. Only four days prior to the reactivation, we performed a regular RXTE monitoring observation. We show the pulse profiles obtained from this observations in Figure 5 (left column). The signal is extremely weak and does not allow detection of pulsations in any of the energy bands except the 2–5 keV.

The reactivation of the source initiated a series of ToO observations whose timing results are presented in Woods et al. (2002). Using the spin ephemeris we determine the profiles shown in Figure 5 (middle column). Even though the change in pulse shape after the April 18 intermediate flare is not as dramatic as the one after the August 27 giant flare, the pulse profile becomes significantly more sinusoidal following this event. In the 2–5 keV profile, we observe one of the broadest single pulse structures ever seen from this source. In July 2001, the long term monitoring campaign observations with RXTE were resumed. We observe significant pulsations only in 2–5 keV profile which is being well described by a single pulse (Figure 5, right column).

Next, we plot the burst activity of SGR 1900+14 (grey histogram) versus the power in the first harmonic (Figure 6 upper panel), as was done for SGR 1806–20. We notice that the pulse in each energy band is strongly sinusoidal after the August 27 flare, while complex before, consistent with previous results (e.g. Woods et al. 2001). We do not have good enough statistics to determine the pulse profile immediately before the April 18 event, however, there is a significant reduction in power at the second harmonic from the year 2000 to post-April 18. In the bottom panel of Figure 6 we plot the PCR of the source over time. We clearly see that the pulsed count rate follows the quiescent source flux trend reported by Woods et al. (2001). The pulsed count rate increases significantly after the August and April large and intermediate flares, respectively; it resumes its background value in all other intervals. We expand on these results in the next section.

4. Discussion

Earlier results (Woods et al. 2001) have shown that the persistent flux of SGR 1900+14 decayed as a power law for almost 40 days following the August 27 flare \( F \propto t^{-0.71} \). We have very good statistics in our data to study the pulsed count rates (PCR) measured during the decay of this event. In Figure 7 (top panel) we expand the tail of the event into ten individual measurements of PCRs in 3 energy bands over a 20-day interval. The horizontal lines in the
Fig. 6.— (upper panel) History of the power in the fundamental (3 energy bands) for SGR 1900+14 along with the burst activity history of this source as seen with BATSE. The horizontal bars at the Fourier power points denote the time spans of each observing cycle. The dotted region starts after the reentry of CGRO. (bottom panel) The history of the rms pulsed count rate in each energy range during the same period.
plot denote the PCR levels in the 2–5 keV (dashed line), 5–10 keV (dot-dot-dot-dashed line) and 10–20 keV (dot-dashed line) during the quiescent state of the source in 1996. Following the giant flare, the values of the PCRs increased by a factor of $\sim 21$, 19, and 7, in the 2–5 keV (PCR$_1$), 5–10 keV (PCR$_2$), and 10–20 keV (PCR$_3$) bands, respectively, over their quiescent levels. The middle and bottom panels of Figure 7 exhibit the ratios of PCR$_1$ to PCR$_2$ and PCR$_1$ to PCR$_3$, respectively. These trends can be interpreted as reflecting the spectral variations of the pulsed emission during the decay of the flare. The PCR$_1$/PCR$_2$ values varied between $1.14 \pm 0.03$ and $1.67 \pm 0.16$, always significantly higher than the non-active episode value of 1.03. There is statistically significant variability in this softness ratio as a function of time, but the changes are relatively small in amplitude ($\lesssim 40\%$). The PCR$_1$/PCR$_3$ ratio (the bottom panel) shows a clear hardening of the spectrum after the first $\sim 3$ days of the decaying tail of the August 27 flare.

Figure 8 describes the decay behavior of the April 18, 2001 intermediate flare from SGR 1900 + 14. The pulsed count rates here increased by a factor of 3.6, 2.6 and 2.2., for PCR$_1$, PCR$_2$, and PCR$_3$, respectively, again with respect to their quiescent values measured in 1996. As we also see in the middle panel, the decay of PCR$_1$ and PCR$_2$ are similar and their ratio is consistent with an average of 1.33, and there is marginal evidence of hardening starting 2 days after the event onset (bottom panel). Overall the soft-to-hard rate ratios are consistent with their quiescent values.

To compare the evolution with energy of the pulsed count rates in both sources, we plot in Figure 9 their PCR$_1$ vs PCR$_2$ (squares) and PCR$_1$ vs PCR$_3$ (triangles). The left panel of Figure 9 exhibits all data points for SGR 1806–20 (filled symbols), together with measurements for SGR 1900+14, when the source was in the same (quiescent) state (open symbols). For SGR 1806–20 we find no correlation neither between PCR$_1$ and PCR$_2$ (filled squares), nor PCR$_1$ and PCR$_3$ (filled triangles).

The right panel of Figure 9 exhibits all our data points for SGR 1900 + 14, in both its quiescent and active states. We find no correlation between PCR$_1$ and PCR$_3$, but we find that PCR$_1$ and PCR$_2$ are strongly correlated with Spearman’s rank order correlation coefficient, $\rho = 0.99$ and the probability of getting such a correlation from a random data set, $P_c = 3.6 \times 10^{-8}$. We noticed, however, that there seems to be a break in the trend at very low values, so we reanalyzed these points separately. We find that a fit to PCR$_1 > 0.2$ yields a slope of $0.91 \pm 0.05$ ($\chi^2 = 1.06$); below this value, the fit has a slope of $0.69 \pm 0.07$ ($\chi^2 = 0.93$). The insert in Figure 9 (right panel) shows the extrapolation of both fits within the dashed line box. PCR$_3$ remains constant above PCR$_1 > 0.2$. We should note here, that all values outside the box belong to the decaying tail of August 27, 1998, while within the box, we have points from the same event as well as following the intermediate flare of April
Fig. 7.— (*top panel*) Plot of pulsed count rate (PCR) decay in 3 energy bands following the August 27 flare. The corresponding energy of each symbol is presented in the legend. The horizontal lines are the PCR values (dashed line in 2–5 keV, dot-dot-dot-dashed line in 5–10 keV and dot-dashed line in 10–20 keV) in 1996 observations when there was no bursting activity. (*middle panel*) The ratio of PCR$_1$ to PCR$_2$ during the same time period. The vertical bars represent the errors associated with ratios and the horizontal bars show the observation time span over which PCRs are determined. The horizontal dotted line shows the PCR$_1$/PCR$_2$ ratio for the non-active episode. (*bottom panel*) The ratio of PCR$_1$ to PCR$_3$. 

\[ \frac{\text{PCR}_1}{\text{PCR}_2} \]

\[ \frac{\text{PCR}_1}{\text{PCR}_3} \]
Fig. 8.— (top panel) Plot of pulsed count rate (PCR) decay in 3 energy bands following the April 18 burst. The corresponding energy of each symbol is presented in the legend. The horizontal lines are the PCR values (dashed line in 2–5 keV, dot-dot-dot-dashed line in 5–10 keV and dot-dashed line in 10–20 keV) in 1996 observations when there was no bursting activity. (middle panel) The ratio of PCR_1 to PCR_2 during the same time period. The vertical bars represent the errors associated with ratios and the horizontal bars show the observation time span over which PCRs are determined. The horizontal dotted line shows the PCR_1/PcR_2 ratio for the non-active episode. (bottom panel) The ratio of PCR_1 to PCR_3.
18, 2001 and the quiescent source emission.

SGR 1900+14 has shown dramatic pulse profile changes on a timescale of minutes associated with burst activity, in particular during and after the giant flares. Unlike SGR 1900+14, changes in the SGR 1806–20 pulse profiles are not drastic, but significant (c.f., those in 1996 and 1999 in Figure 1). Since our RXTE observations in 1996 ended before the peak of burst activity from this source was recorded with BATSE, we looked at the energetics of bursts seen with BATSE after the end of the RXTE data. The energy of BATSE events seen during the RXTE coverage comprise only ~ 5% of the total energy ($E_{\text{TOT,BATSE}}$) of all events seen with BATSE over ~ 4 years (starting in 1996). Interestingly, bursts detected over the next ~ 5 days following our last RXTE observations in 1996 contained ~ 40% of $E_{\text{TOT,BATSE}}$. The later (1999) simplification of the pulse profile of SGR 1806–20 may, therefore, have its onset during this intense burst active phase in 1996, similar to the effect of the 1998 August 27 giant flare in the pulse profile of SGR 1900+14.

5. Conclusions

We have performed a detailed analysis of the persistent X-ray pulsed flux data from two Soft Gamma Repeaters, SGR 1900+14 and SGR 1806-20. In both sources, we find a strong trend of their pulse shapes to transition from complex to very smooth, following burst active episodes. Our analysis of the decaying tail of the 27 August giant flare from SGR 1900+14, has shown that as the persistent source spectrum softened, the pulse count rates in the 2-5 keV band varied in tandem with those of the 5-10 keV; the 10-20 keV pulsed count rates remained constant, albeit slightly above their pre-flare values. Further, we observe a change in the correlation slope of the pulsed count rates in the lower energy ranges (2-5, and 5-10 keV) during quiescence or low activity of the source, suggesting that the 2-5 keV photons are more efficiently produced during non-burst active periods.

Recently, Thompson, Lyutikov & Kulkarni (2002; TLK hereafter) have suggested a model, whereby the persistent X-ray emission of a magnetar is due to currents generated when the interior magnetic field twists up the external magnetic field. The structure we observe in the pulse profile of SGRs could then be attributed to a complicated distribution of currents and magnetic fields close to the neutron star (higher multipoles) seen through a largely transparent magnetosphere. However, the observed transition of complex to smooth in the pulse profiles is not accompanied by spectral and intensity changes, as would be expected in that case from a simplified magnetic field (current) after the source returns to its quiescent flux level. Alternatively, re-scattering of the X-rays either at $R > 100$ km by non-axisymmetric currents, or at 100 km by plasma suspended against gravity by the resonant
Fig. 9.— (left panel) Plot of PCR$_1$ vs PCR$_2$ (filled squares) and PCR$_1$ vs PCR$_3$ (filled triangles) for SGR 1806–20. The open symbols in this plot are those of SGR 1900+14 values measured during non active episodes. (right plot) Plot of PCR$_1$ vs PCR$_2$ (squares) and PCR$_1$ vs PCR$_3$ (triangles) for SGR 1900+14. The inset is the zoomed view of dashed box at the low end of PCR values. The solid line represents the best fit model to values with PCR$_1 > 0.2$. The solid line within the inset is the best fit model to PCR$_1 < 0.2$ values and the dashed line is the extrapolation of previous fit results.
e⁻ scattering force, may be the cause of the profile smoothness. The apparent difficulty to retain the suspended plasma in the magnetosphere (it would be quickly drained to the neutron star surface by even a modest electrical current), points towards the re-scattering screen above 100 km as the most plausible of these two explanations for the transition. The current then would in principle be generated by a static twist (TLK 2002), consistent with the observed absence of a direct correlation between the increase in the neutron star spin (torque) with burst activity (Woods et al. 2002).

Concluding, we believe that our results provide evidence for an association of the complex (smooth) profile of the SGR pulses with the re-scattering of X-rays above 100 km from the neutron star surface, depending on whether the currents created by the static twist described by TLK (2002) are non-axisymmetric (axisymmetric). The rapid spindown observed in SGRs should then be coupled to the smoothening of their pulse profiles; we are currently investigating further correlations between all these SGR properties.

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### Table 1: RXTE PCA observations of SGR 1806–20.

| Epoch | Date Ranges  | No. of Obs. | Exposure (ks) |
|-------|--------------|-------------|---------------|
| 1996  | 96/11/07–96/11/18 | 12          | 132.4         |
| 1999  | 99/01/16–99/08/08 | 43          | 297.9         |
| 2000  | 00/03/14–00/11/23 | 87          | 254.4         |
| 2001  | 01/07/02–01/07/22 | 12          | 37.5          |

| Epoch | Date Ranges  | No. of Obs. | Exposure (ks) |
|-------|--------------|-------------|---------------|
| 1999  | 01/07/02–01/07/22 | 12          | 37.5          |

### Table 2: RXTE PCA observations of SGR 1900+14.

| Epoch | Date Ranges  | No. of Obs. | Exposure (ks) | Notes\(^a\) |
|-------|--------------|-------------|---------------|-------------|
| 1996  | 96/09/04–96/09/20 | 19          | 97.7          | J1906(A), 1907 |
| May 98 | 98/05/31–98/06/09 | 5           | 43.5          | J1906(Q)     |
| Aug 98 | 98/08/28–98/08/31 | 10          | 33.2          | J1906(Q)     |
| SepOct 98 | 98/09/01–98/10/08 | 30         | 126.2         | J1906(A)     |
| 1999  | 99/01/03–99/07/28 | 41          | 293.1         | J1906(Q), 1907 |
| 2000  | 00/06/08–00/12/24 | 93          | 435.6         | J1906(Q), 1907 |
| Pre-Apr 2001 | 01/04/14 | 1           | 9.6           | J1906(N/A)   |
| Post-Apr 2001 | 01/04/19–01/05/01 | 13         | 111.1         | J1906(N/A)   |
| July 2001 | 01/07/04–01/07/25 | 22         | 81.5          | J1906(N/A)   |

\(^a\) Presence of XTE J1906+09 or 4U 1907+09 within the PCA field of view. In parenthesis A, Q and N/A denote transient activity, quiescence and information not available, respectively.