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Understanding AXPs and SGRs through the December 2004 SGR 1806–20's Hyperflare

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Abstract On 27th December 2004 SGR 1806–20, one of the most active Soft γ-ray Repeaters (SGRs), displayed an extremely rare event, also known as giant flare, during which up to 10^{47} erg were released in the $\sim$1–1000 keV range in less than 1s. Follow-up *VLA* observations after the giant flare largely increased the position accuracy of SGR 1806–20, allowing to perform sensitive searches at shorter wavelengths. In particular we carried out observations by using IR adaptive optics (*NAOS-CONICA*) mounted on *VLT* which provided images of unprecedented quality (FWHM better than 0.1$''$). We discovered the likely IR counterpart to SGR 1806–20 based on positional coincidence with the *VLA* uncertainty region and flux variability of a factor of about 2 correlated with that at higher energies.
Among the several high energy datasets obtained during the 27th December 2004 event, we analyzed those taken from the *Rossi–XTE* which provided the highest ever statistics for a giant flare. We discovered rapid Quasi Periodic Oscillations (QPOs) in RXTE/PCA data of the pulsating tail of the 27th December 2004 giant flare. QPOs at $\sim$92.5 Hz are detected in a 50 s interval starting 170 s after the onset of the giant flare. This is the first time that QPOs are unambiguously detected in the flux of a Soft Gamma-ray Repeater, or any other magnetar candidate. We interpret the highest QPOs in terms of the coupling of toroidal seismic modes with Alfvén waves propagating along magnetospheric field lines.

Key words: stars: neutron — stars: oscillations — pulsars: individual: SGR 1806–20 — infrared: stars — X-rays: bursts

1 INTRODUCTION

Soft Gamma-ray Repeaters (SGRs) are characterized by short and recurrent bursts ($<$1 s) of soft γ rays. Only four confirmed SGRs are known, three in the Galaxy and one in the Large Magellanic Cloud (see Woods & Thompson 2004 for a recent review). The nature of SGRs has remained a mystery for many years. The $\sim$ 8 s periodicity clearly seen in the tail of the 1979 March 5th giant flare of SGR 0526–66 suggested an association of SGRs with neutron stars. Several observational properties of SGRs are successfully modelled in terms of "magnetars", isolated neutron stars in which the dominant source of free energy is their intense magnetic field ($B \sim 10^{14}$–10^{15} G; Duncan & Thompson 1992; Thompson & Duncan 1995).

Bursting activity from SGR 1806–20 resumed at the end of 2003 displaying an increase in both the γ-ray burst rate and the hard X-ray persistent emission (Mereghetti et al. 2005) throughout 2004, and culminating with the giant flare of 27th December 2004 (Borkowski et al. 2004, during which $\sim 10^{47}$ erg were released (for a distance of about 10 kpc; Cameron et al. 2005; McClure-Griffiths & Gaensler 2005). Few days after this event, SGR 1806–20 was detected in the radio band for the first time, providing a very accurate position (VLA; Cameron et al. 2005; Gaensler et al. 2005a).

Thanks to a Target of Opportunity (*ToO*) observational campaign on SGR 1806–20 carried out during 2004 with the *ESO VLT* we likely discovery of the IR counterpart to SGR 1806–20 based on positional

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coincidence with the radio position and flux variability. Moreover, based on serendipitous high–time resolution data obtained with the Rossi X-ray Timing Explorer (*RXTE*) Proportional Counter Array (PCA), we carried out the first detailed X-ray timing analysis of the 2004 December 27th hyperflare of SGR 1806–20, and we discovered rapid quasi periodic oscillations (QPOs) in its X-ray flux few minutes after the onset of the giant flare.

2 VLT NAOS–CONICA IR OBSERVATIONS

The data were acquired at *VLT* with the Nasmyth Adaptive Optics System and the High Resolution Near IR Camera (*NAOS-CONICA*). Data were reduced following standard procedures for photometry and astrometry (see Israel et al. 2005a for details of the observations and data reduction).

Source A, a relatively faint (Ks$\sim$20) object, at the sky position R.A.= $18^{\rm h}$ $08^{\rm m}$ $39\overset{\rm s}{.}337$, Dec.= -20° $24'$ $39\farcs85$ (equinox 2000, 90% uncertainty of $0\farcs06$), is found to be consistent with the *Chandra* and *VLA* positional uncertainty circles superimposed on our IR astrometry-corrected frame (see Figure 1). Objects B and C ($\sim 0\farcs23$ and $0\farcs27$ away from A, respectively) are only marginally consistent with the X-ray and radio positions, even though statistically plausible. Light curves of the A, B and C objects are shown in Figure 1 (right plot). Candidate A is the only one showing a clear brightening (a factor of $\sim$2) in the IR flux between June and October 2004 (see Israel et al. 2005a for more details).

Both the *XMM-Newton* (Mereghetti et al. 2004) and *INTEGRAL* (Mereghetti et al. 2005) persistent fluxes of SGR 1806–20 showed an increase across the two semesters of 2004 by a factor of $1.94^{+0.01}_{-0.02}$ and $1.7^{+0.4}_{-0.3}$ in the 2–10 keV and 20–100 keV bands, respectively. During the same time interval the *NAOS–CONICA* Ks flux increased by a factor of $2.4^{+0.9}_{-0.5}$, consistent with high energy flux variations, supporting the identification of object A as the correct IR counterpart of SGR 1806–20.

3 RXTE OBSERVATION OF THE DECEMBER 2004 GIANT FLARE

The giant flare of SGR 1806–20 was serendipitously recorded at 21:31:30.7 UT on 2004 December 27th. The PCA was observing in its GoodXenon mode, resulting in full timing ($\sim$ 1 μs) covering the nominal energy range $\sim$2–120 keV. We restricted our timing analysis to the gap-free interval, starting 12.8 s after the onset of the initial spike. We accumulated a light curve from all PCA channels with a resolution of 1/256 s (a 0.5 s binned light curve is shown in Figure 2).

A peak in the power spectra around 90 Hz was detected around 170–220 s from T_0 (see Figure 3 and Israel et al. 2005b for the analysis details).

The peak shown in Figure 3d has a centroid frequency of 92.5 $\pm$0.2 Hz, a FWHM of $1.7^{+0.7}_{-0.4}$ Hz (uncertainties are at 1σ confidence level), and a signal coherence of Q$\sim$50. The integrated fractional rms of the peak was 7.3 $\pm$0.7%, and a chance probability, calculated by using the prescription of Israel & Stella (1996), of $\sim 1.5{\times}10^{-5}$ – $1.3{\times}10^{-4}$ after normalization for the number of trial periods (128–1024) over which the search was carried out. We thus consider rather robust the 92.5 Hz QPO detection.

Selecting 3 phase intervals centered around the main peak at phase $\sim$ 0.4, the second peak at phase $\sim$ 0.7, and the minimum around phase 0, it is evident that the 92.5 Hz oscillations are absent in the main peak (3σ upper limit of 4.1% rms) clearly detected in the minima (rms amplitude of 10.7 ± 1.2%) and still present, though at a lower significance, in the second peak (rms amplitude of 8.0 ± 0.9%; see panels *e*, *f* and *g* of Figure 3).

In order to check for correlations which might provide clues on the origin of the oscillations we study the 92.5 Hz QPOs with respect to the other timing parameters of the hyperflare. Figure 2 shows the result of this analysis where the PCA light curve is overimposed to some of these parameters: the DC level (gray filled circles), the count rates of the main peak (gray filled squares), of the second peak (light dark filled squares) and of all components together (filled stars). From the comparison between Figure 3 and Figure 2 it is evident that the time interval over which the 92.5 Hz QPOs are significantly detected coincides with a bell-shape enhancement in the DC level about 200 s after the beginning of the flare. Moreover, it is apparent that the intensity of the DC level and that of the main peak of the pulse are anti-correlated (the first peak component shows a marked decrease corresponding to the rise of the bell-shaped intensity bump of the DC), likely implying two distinct emission components. It is also worth noting that the hardness ratio (HR) between the 1–9 keV and 9–25 keV nominal energy band light curves shows that the pulse minima are always softer than peaks, except during the bell-shaped bump where minima are as hard as the maxima

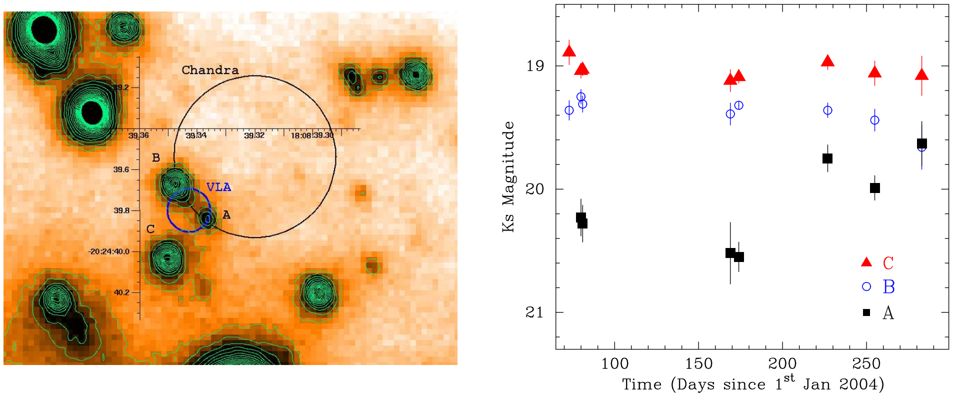

Fig. 1 *NAOS-CONICA* Ks band image (left panel) of the $1''.5 \times 1''.5$ portion of the sky around the 1σ *Chandra* and *VLA* uncertainty circles (radius of $0''.3$, $0''.04$ and $0''.1$, respectively) with the proposed counterpart marked with A. Ks light curves (right panel) of the proposed counterpart to SGR 1806–20 (A) with two nearby objects.

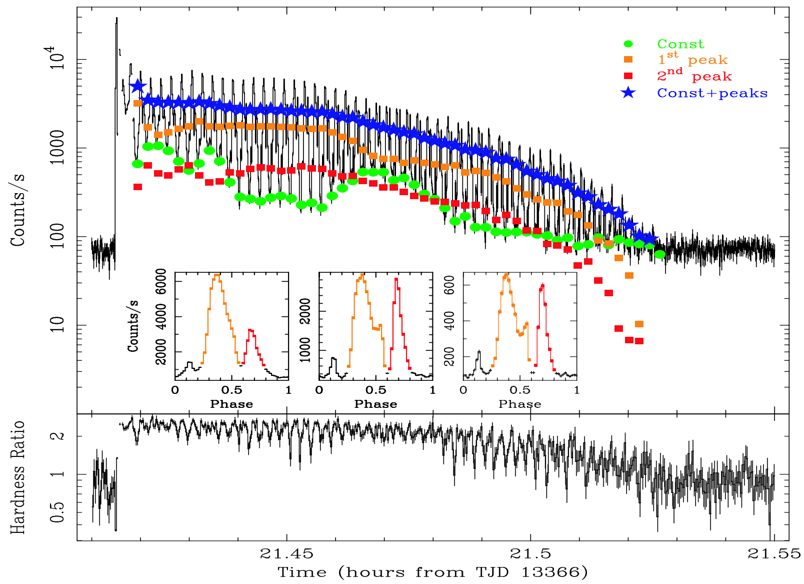

Fig. 2 The *RXTE* PCA 0.5 s binned light curve of the SGR 1806–20 hyperflare (upper panel). Overimposed are four parameters resulting from the fitting of each 7.56 s pulse with a constant plus five Gaussian model: the DC level (gray filled circles), the intensity of the main peak (gray filled squares), of the second peak (light dark filled squares), and of all components (filled stars). The three insets show the average pulse shapes as a function of time with the two main peak marked in gray and light dark lines. Time intervals over which the light curve have been folded are approximatively those where insets lie (before, during and after the gray region of Figure 3b). Lower panel represents the PCA 9–25 keV over 1–9 keV energy band light curve ratio (see text for details).

(see lowest panel of Figure 2). These findings clearly suggest that the bell-shaped bump in the decaying pulsating tail of the SGR 1806–20 hyperflare represents an additional unpulsed component underlying the main pulse component.

From Figure 3a, one can see also a significant amount of power in the 20–30 Hz interval. Therefore, we subdivided the light curve into smaller intervals and checked for significant signal below 40 Hz. A fit

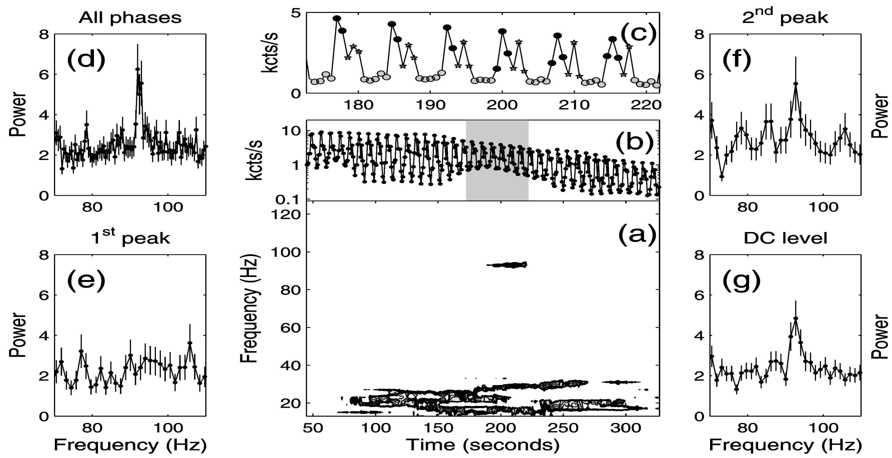

Fig. 3 The ∼92 Hz oscillation as seen by the PCA. (a) Spectrogram with 2 s time step and resolution. The contours represent Leahy powers from 3.2 to 3.7; (b) Light curve corresponding to the same time axis as panel (a). The time resolution is 0.75 s. The gray–shaded area indicates the time interval shown in panel (c); (c) Close–up of the gray area in panel (b). The different symbols mark the first peak (black circles), the second peak (stars) and the DC level (gray circles); (d) average power spectrum (at 0.5 Hz resolution) of the gray area in panel (b); (e) average power spectrum (at 1.33 Hz resolution) of the phase interval including the first peak as seen in panel (c); (f) same as (e) for the second peak; (g) same as (e) for the DC level.

to the continuum (constant plus a power-law) yields two QPOs at 18.1±0.3 Hz and 30.4±0.3 Hz with a single trial significance of 3.6 and 4.7σ, respectively. A weak excess is also visible at $\sim$ 95 Hz, indicating a possible time evolution of the $\sim$ 92.5 Hz QPO frequency.

4 DISCUSSION

The deep and high spatial resolution *NAOS-CONICA* images allowed us to identify the likely IR counterpart of SGR 1806–20, and to monitor its IR flux for seven months in 2004, during which an increase by a factor of $\sim$ 2 was detected, correlated with the flux in the high energy bands.

It is worth noting that a similar IR variability correlated with X-rays has been found also for three Anomalous X-ray Pulsars, namely 1E 1048.1−5937, XTE J1810−197 and 1E 2259+586 (Israel et al. 2002; Rea et al. 2004; Tam et al. 2004).

We note that the SGR 1806–20 emission varies in a similar fashion (in terms of timescale and amplitude of variation) over more than five orders of magnitude in photon energy. The similar flux variation in the IR and X-ray bands suggests that the emission in the two bands has a similar, if not the same, origin. Moreover, it has become evident that X-ray flux enhancement of the persistent emission of SGRs is correlated with their burst rate (see Woods & Thompson 2004), and related with IR enhancement of magnetospheric origin (Tam et al. 2004). Alternatively, the IR flux can be due to reradiation by material in the vicinity of the the pulsar. This model naturally predicts a correlation between the the IR and the X-ray flux (Perna, Hernquist & Narayan 2000; Rea et al. 2004).

We discovered rapid quasi periodic X-ray oscillations in the evolving X-ray flux of the 2004 Dec 27th hyperflare of SGR 1806–20, the first ever for a magnetar candidate. The higher frequency QPOs at $\sim$ 92.5 Hz were detected in association with an emission bump that occurred in the DC component. These QPOs were detected only in the spin phase intervals away from the main peak and reached maximum amplitude corresponding to the DC component phase intervals. Evidence for $\sim$ 18 and $\sim$ 30 Hz QPOs was found between 200 and 300 s from the onset of the hyperflare.

In the context of the magnetar scenario, the main spike of the giant flare arises from a fireball of pair-dominated plasma that expands at relativistic speeds, while the energy deposited in the magnetosphere can give rise to a “trapped fireball” that remains confined to the star’s closed magnetic field lines. The long pulsating tail of giant flares probably arises from the cooling of plasma that remains confined in such a trapped fireball. Indeed, a variety of seismic modes are expected to be excited as consequence of the magnetically-induced large scale fracturing of the crust which gives rise to giant SGR flares.

Out of the variety of non-radial neutron star modes studied by McDermott et al. (1988), there are several classes that have characteristic frequencies in the $\sim$ 10–100 Hz range. Toroidal modes appear to be especially promising because they should be easily excited by the large crustal fracturing. Indeed, a large ($\sim$5 km) crustal fracturing on the surface of SGR 1806–20 was inferred from a $\sim$ 5 ms rise timescale observed during the onset of the hyperflare (Schwartz et al. 2005). The fundamental toroidal mode of a rigid neutron star’s crust corresponds to a period of $\sim$ 33.6 ms, somewhat dependent on the mass, radius and crustal magnetic field (McDermott et al. 1988, Duncan 1998). Therefore, the 30.4 Hz ($\sim$ 32.8 ms) oscillation could be easily identified with the ${}_2t_0$ mode, and the 92.5 Hz ($\sim$ 10.8 ms) QPO would thus correspond to a higher harmonic: indeed, it matches well the expected frequency of the l=7 mode, suggesting a relatively small-scale structure in the seismic wave pattern (and thus the magnetic multipole structure).

The 18 Hz oscillation, on the other hand, might be associated with a different mode which must couple to the magnetosphere as well. A poloidal component of the core magnetic field supports a torsional mode with a frequency $\nu_{\rm core} \simeq 2.5 B_{\rm z,15}$ Hz (Thompson & Duncan 2001) with $R \sim$ 10 km and a core density $\simeq 10^{15}$ g cm^{-3}, $B_{\rm z,15}$ being the core poloidal field in units of 10^{15} G: a strong $B_{\rm z,15} \simeq 7$ would be required to match the observed 18 Hz. Although extremely strong, such a field is fully plausible given that a (mainly toroidal) field in excess of 10^{16} G is required to power repeated giant flares of this magnitude over the $\sim 10^4$ yr lifetime of an SGR.

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References

Borkowski, J., Götz D., Mereghetti, S., et al. 2004, GCN #2920
Cameron, P.B., Chandra, P., Ray, A., et al. 2005, Nature, 434, 1112
Duncan, R. C. 1998, ApJ, 498, L45
Duncan, R. C., & Thompson, C. 1992, ApJ, 392, L9
Feroci M., et al. 1999, ApJ, 515, L9
Gaensler, B. M. et al. 2005a, GCN #2929
Israel, G. L., & Stella, L. 1996, ApJ, 468, 369
Israel, G. L., Covino, S., Stella, L., et al. 2002, ApJ, 580, L143
Israel, G. L., et al. 2005a, ApJ, 628, L53
Israel, G., et al. 2005b, A&A, 438, L1
McClure-Griffi ths, N. M., & Gaensler, B. M. 2005, ApJ, submitted, astro–ph/0503171
McDermott, P. N., Van Horn, H. M., & Hansen, C. J. 1988, ApJ, 325, 725
Mereghetti, S., Götz, D., Andersen, M. I., et al. 2005a, A&A, 433, L9
Mereghetti, S., Tiengo, A., Esposito, P., et al. 2005b, ApJ, 628, 938
Perna, R., Hernquist, L., & Narayan, R. 2000, ApJ, 541, 344
Rea, N., Testa, V., Israel, G. L., et al. 2004, A&A, 425, L5
Schwartz, S. J., et al. 2005, ApJ, 627, L129
Tam, C. R., Kaspi, V. M., van Kerkwijk M. H., & Durant, M. 2004, ApJ, 617, L53
Thompson, C., & Duncan, R. C. 1995, MNRAS, 275, 255
Thompson, C., & Duncan, R. C. 2001, ApJ, 561, 980
Woods, P. & Thompson, C. 2004, in “Compact Stellar X-ray Sources”, eds. W. H. G. Lewin & M. van der Klis, astro-ph/0406133