

## **A tremendous flare from SGR1806-20 with implications for short-duration gamma-ray bursts**

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**Soft gamma-ray repeaters (SGRs) are X-ray stars which emit numerous short-duration (about 0.1 s) bursts of photons up to 100 keV during sporadic active periods. They are thought to be *magnetars*: neutron stars with observable emissions powered by magnetic dissipation. Here we report the detection of a rare 380 s long giant flare from SGR1806-20 on 27 December 2004, with energy greatly exceeding that of all previously-detected events. Its initial gamma-ray spike had a blackbody spectrum, characteristic of a relativistic pair/photon outflow. It carried away as much energy in 0.2 second as the Sun radiates in a quarter million years. This extreme energy suggests a catastrophic instability on a magnetar involving global crust failure and magnetic reconnection, perhaps with a significant large-scale untwisting of the magnetosphere. From a great distance this event would appear to be a short-duration, hard spectrum cosmic gamma-ray burst. We argue that this may partially explain the origin of one class of mysterious bursts. NASA's newly-commissioned *Swift* satellite is likely to detect extragalactic magnetars in significant numbers, opening up a new field of astronomical study.**

In the magnetar model, soft gamma repeaters are isolated neutron stars with surface magnetic dipole fields  $B \sim 10^{14} - 10^{15}$  G and even stronger fields within<sup>1, 11</sup>. This would make them the objects with the strongest known magnetic fields in the universe. A variety of evidence seems to support this hypothesis. For example, SGRs are periodic soft X-ray sources with high spindown rates<sup>10,12</sup> which, if attributed to magnetic torques, require ultrastrong magnetism.

Only four SGRs are known: 3 in our Galaxy, and one in the Large Magellanic Cloud. Two of them have emitted long-duration (several hundred seconds) *giant flares*<sup>2,3</sup>, which commenced with brief ( $\sim 0.2$  s) *hard spikes* of photons up to MeV energies, followed by *tails* lasting minutes, during which hard X-ray emissions gradually faded

while oscillating on the rotation period of the neutron star. These giant flares give important clues about the nature of SGRs, as we will highlight in this paper.

The first known giant flare was observed on 5 March 1979. Its fluence implied an energy  $> \sim 6 \times 10^{44}$  erg at a distance of 50 kpc, as suggested by the source's sky position within supernova remnant N49 in the Large Magellanic Cloud<sup>4</sup>. The flare tail oscillated with an 8.1 s period<sup>2,5</sup>, the putative rotation period of the flaring star, SGR 0526-66<sup>1,13</sup>. The second known giant flare came from SGR1900+14 on 27 August 1998,<sup>3</sup> and had a 5.16 s period. Its energy was  $2 \times 10^{44}$  erg for an assumed distance of 15 kpc<sup>7</sup>. Here we present X- and gamma-ray observations of a greatly more energetic giant flare which came from SGR1806-20. We show that its characteristics may be explained by a global magnetic instability. In addition we discuss the implications of this event for the hitherto-unexplained short-duration, hard spectrum cosmic gamma-ray bursts.

### **Characteristics of the giant flare from SGR1806-20**

On 27 December 2004, the International Gamma-Ray Astrophysics Laboratory<sup>40</sup> (INTEGRAL) reported the detection of the third giant flare to date; it was also observed by 4 other missions in the 3<sup>rd</sup> interplanetary network of gamma-ray burst detectors (the High Energy Neutron Detector and Gamma Sensor Head aboard Mars Odyssey<sup>37</sup>, the solar-pointing Reuven Ramaty High Energy Solar Spectroscopic Imager<sup>38</sup> (RHESSI), Wind<sup>39</sup>, and Swift<sup>41</sup>). It was preceded by a  $\sim 1$  s long precursor. The giant flare commenced with an intense spike of duration  $\sim 0.2$  s, followed by pulsating tail which was observed for  $\sim 380$  s. The profiles are shown in Figure 1. Arrival time analysis, or triangulation, constrains the arrival directions of both the precursor and the giant flare to a portion of a narrow annulus whose position is consistent with that of SGR1806-20 (annulus center J2000 right ascension 15 h 56 m 37 s, declination  $-20^\circ 13' 50''$ , annulus radius  $30.887 \pm 0.030$  °). This position is inconsistent with the positions of any other

known or candidate SGRs. SGR1806-20 was approximately  $5^\circ$  from the Sun at the time of these observations.

The precursor, which occurred 142 s before the giant flare, exhibited a rise time  $\sim 45$  ms and a fall time  $\sim 150$  ms. The profile (inset to Fig. 1) can be described as roughly flat-topped. Its  $>3$  keV keV fluence was  $1.8 \times 10^{-4}$  erg  $\text{cm}^{-2}$ , and its energy spectrum can be crudely approximated by an optically thin thermal bremsstrahlung function with  $kT \sim 15$  keV. For an assumed distance of 15 kpc (ref. 15), its luminosity was  $4.6 \times 10^{42}$  erg.

The initial peak of the giant flare had rise and fall times  $<1$  ms and  $\sim 65$  ms respectively, similar to those for the other giant flares<sup>2,9</sup>. Its intensity was such that all X- and gamma-ray detectors were briefly driven into saturation, but measurements with the RHESSI particle detectors are consistent with a fluence above 30 keV of  $1.36 \pm 0.35$  erg  $\text{cm}^{-2}$ , making this the most intense cosmic transient observed in over 25 years of monitoring. Its peak flux as observed at earth outshone even the brightest solar flares. The time-resolved energy spectrum is consistent with that of a cooling blackbody (figure 2) whose average temperature is  $T_{\text{spike}} = 175 \pm 25$  keV. At 15 kpc (ref. 15), the energy would have been  $E_{\text{spike}} = 3.5 \times 10^{46}$  erg and the peak flux in the first 0.125 s would have been  $L_{\text{spike}} = 1.8 \times 10^{47}$  erg  $\text{s}^{-1}$ . Comparisons with previous giant flares are subject to numerous uncertainties due to the variety of instruments, energy ranges, and time resolutions, but this flare was over 100 times more energetic than any observed previously in our Galaxy.

The peak was followed by a hard X-ray tail modulated with a period of 7.56 s, detected by RHESSI for 380 s. This period agrees with the neutron star rotation period as inferred from cyclic modulations of the quiescent soft X-ray source<sup>10</sup>. The fluence above 3 keV in this phase is  $4.6 \times 10^{-3}$  erg  $\text{cm}^{-2}$  or  $E_{\text{tail}} \approx 1.2 \times 10^{44}$  erg.

## Magnetar interpretation

This event can be understood as a catastrophic instability of a magnetar. Strong shearing of the neutron star's magnetic field, combined with growing thermal pressure, appears to have forced an opening out of the field, launching a hot fireball. The release of energy above a rate of  $\sim 10^{42}$  erg/s (less than one part in  $10^{-4}$  of the peak flare luminosity) leads to the formation and of a hot, thermal pair plasma ( $kT \sim 0.1$ -1 MeV).<sup>16</sup> The fast initial rise  $\tau_{rise} \leq 1$  ms is consistent with a magnetospheric instability with characteristic time  $\tau_{mag} \sim (R / 0.1 V_A) \sim 0.3$  ms, where  $R \sim 10$  km and  $V_A \sim c$  is the Alfvén velocity in the magnetosphere.<sup>11</sup> This process must have occurred repeatedly, given that the hard initial spike persisted for a duration  $\sim 10^3 \tau_{mag}$ . The resulting outflow emitted a quasi-blackbody spectra as it became optically thin, with spectral temperature comparable to the temperature at its base, since declining temperature in the outflow is compensated by the relativistic blueshift.<sup>42</sup> For luminosity  $L_{spike} = 10^{47} L_{47}$  erg s<sup>-1</sup> emerging from a zone of size  $R \sim 10$  km, the expected spectral temperature is  $T_{spike} = (L_{spike} / 4\pi acR^2)^{1/4} = 200 L_{47}^{1/4}$  keV, neglecting complications of magnetospheric stresses and intermittency. Almost all the pairs annihilated, and the outflow was only weakly polluted by baryons, as is evinced by the extended, weak radio afterglow that followed the flare (see ref. TBD in this issue). Note that there is no expectation for significant beaming of such powerful emissions from such a slowly-rotating star.

When the outflow ceased, a *trapped fireball* was evidently left behind: an optically-thick photon-pair plasma confined by closed field lines near the star<sup>11,16</sup>. This zone of plasma diminished in size as pairs annihilated in its outer, cooling layers, radiating away its energy and evaporating in a finite time. This picture is corroborated by our fit of the rotation-smoothed light curve of the flare's tail ( Fig. 3) to the fireball function<sup>30</sup>.

$L_x(t) = L_O [1 - (t / t_{evap})]^{a/(1-a)}$  for  $t_{evap} = 382 \pm 3$  s, and for index  $a = 0.606 \pm 0.003$  near

the value  $a = 2/3$  expected for a homogeneous, spherical trapped fireball<sup>16,30</sup>. The condition that the magnetic field must be strong enough to confine energy  $E_{tail}$  within a distance  $\Delta R \sim 10$  km of the star yields a rough bound on the dipole field,  $B_{dipole} > 2 \times 10^{14} (\Delta R / 10 \text{ km})^{-3/2} [(1 + \Delta R / R) / 2]^3$  G, similar to bounds implied by the previous giant flares<sup>3,11</sup>.

What was the cause of this tremendous instability? An important clue is provided by the spike's  $\sim 0.2$  second duration. This is close to the durations of other giant flare spikes as well as the more common (and much less luminous) SGR bursts, whose durations cluster around  $\sim 0.2$  s across some four orders of magnitude in energy<sup>25</sup>. In the magnetar model, the activity of an SGR is thought to result from the unwinding of a strong, toroidal magnetic field inside the deep crust and core, and the transfer of magnetic helicity across the surface of the star<sup>16,28</sup>. Such a twist propagates along the poloidal magnetic field  $B_p = 10^{15} B_{p15}$  G with a speed  $V_A \approx B_p / \sqrt{4\pi\rho}$  that is weakly dependent on the twist amplitude. The time to cross the neutron star interior (density  $10^{15} \rho_{15} \text{ g cm}^{-3}$ ) is  $\Delta t \sim 2R / V_A \sim 0.2 B_{p15}^{-1}$  s.

Thus the December 27 event could have been a crustal instability which drove helicity from the star<sup>16,28</sup>. The unwinding of a toroidal magnetic field imbedded in the crust is strongly impeded by the stable stratification<sup>16</sup>. Because of the energetic cost of forming isolated dislocation surfaces which cross the magnetic flux surfaces, the crust must undergo smooth, (vertically) differential torsional motion when it fails, which requires a fundamental breakdown of its solid structure. The maximum toroidal magnetic field which can be stored in the crust is related to the yield strain via

$B_{\phi \text{ max}} = 1 \times 10^{16} (\theta_{\text{max}} / 10^{-2}) B_{p15}^{-1}$  G. The energy in this toroidal field is easily

sufficient to power the December 27 flare if the yield strain is as high as  $\sim 10^{-2}$ . The enormous peak luminosity of the December 27 flare requires a twist of the crust with an angular displacement approaching  $\sim 0.5 B_{p15}^{-1}$  radian.

A related possibility is suggested by recent observations of SGR 1806-20. Since March 2004, SGR 1806-20 has been very burst-active<sup>31</sup> while its X-ray brightness has increased by a factor 2-3, and its spectrum hardened dramatically<sup>32</sup>. Evidently, crust failure has enhanced the twist in the external magnetic field, with growing magnetospheric currents<sup>28</sup>. The free energy of such an exterior magnetic twist can reach a modest fraction ( $\sim 10^{-1}$ ) of the untwisted exterior dipole field energy,  $E_{twist} \sim 10^{-2} B_{dip}^2 R^3 \sim 10^{46} B_{p,15}^2$  erg, with more energy in the non-potential components of higher multipoles. Some of this energy could be catastrophically released via reconnective simplification of the magnetosphere<sup>28,29</sup>. An extreme possibility, consistent with the flare energy, is a global magnetospheric untwisting. This would predict a dramatic post-flare drop in the stellar spin-down rate, as well as greatly diminished, softened and less strongly-pulsed X-ray emissions. However, a *pure* magnetospheric instability would proceed much faster than  $\sim 0.2$  s. Moreover, the detection of accelerated spin-down several months following previous active periods of SGRs 1806-20 and 1900+14<sup>27</sup> betrays a net *increase* in the magnetospheric twist during the X-ray bursts, and in the 1998 August 27 giant flare. Observations of spin-down in SGR 1806-20 over the coming year will provide important constraints on the location of the non-potential magnetic field which was dissipated during the December 27 flare, a significant fraction of which may have resided outside the star.

### **Short duration GRBs and magnetar flares**

If observed from a great distance, only the brief, initial hard spike of the December 27 flare would be evident. Thus distant extragalactic magnetar flares (MFs) would resemble the mysterious short-duration gamma ray bursts (GRBs)<sup>53</sup>. These hard-spectrum events have long been recognized as a separate class of GRBs<sup>19,20,21,22,23</sup> but never identified with any counterpart<sup>24</sup>.

The Burst and Transient Source Experiment (BATSE) on the *Compton Gamma Ray Observatory* was a landmark experiment of the 1990's that produced a catalog<sup>45</sup> of more than 2000 GRBs. How many of these bursts were MFs? Taking the December 27 event as our prototype and adopting the 50% trigger-efficiency flux<sup>33</sup> of  $0.5 \text{ ph cm}^{-2} \text{ s}^{-1}$  for the 256 ms timescale yields a BATSE sampling depth  $D_{\text{BATSE}} = 30 \text{ Mpc}$ . If such events generally happen once every  $\tau = 30 \text{ yr}$  in galaxies like the Milky Way (as has now occurred in the Milky Way itself) then the BATSE detection rate of MFs is  $\dot{N}(\text{BATSE}) = 19(\tau/30 \text{ yr})^{-1} \text{ yr}^{-1}$ . Here we have estimated the effective number of galaxies like the Milky Way within  $D_{\text{BATSE}}$  of Earth by multiplying the local blue luminosity density<sup>45</sup>  $j_{\text{Bj}} = 5.8 \times 10^{41} h_{70} \text{ erg Mpc}^{-3}$  by the sampling volume  $(4\pi/3)D_{\text{BATSE}}^3$ , and dividing by the blue luminosity of the Milky Way as estimated in the Methods section below. We use blue emissions as our benchmark because SGRs are Pop. I objects, the post-supernova remnants of massive, short-lived, blue stars. Thus over 9.5 years of operation with half-sky coverage, BATSE likely detected  $180(\tau/30 \text{ yr})^{-1}$  MFs, representing  $0.4(\tau/30 \text{ yr})^{-1}$  of all BATSE short-duration bursts. There is evidence of 100-s long soft tails in the co-added time histories of many BATSE GRBs<sup>51,52</sup>; but not in any single GRB. For the brightest observed BATSE short-hard GRB, trigger #6293, we find the ratio of the tail-to-peak fluence is  $<0.5\%$ , compared to our measured ratio for the December 27 event of  $0.34\%$ . Thus BATSE was not sensitive enough to have detected MF tails in single events.

NASA's recently-launched *Swift* GRB observatory<sup>34</sup> was designed, in part, to unravel the short GRB mystery. How many MFs will *Swift* spot? The *Swift* Burst Alert Telescope has (50-300 keV) photon flux sensitivity  $\sim 5$  times better than BATSE<sup>46</sup>,

corresponding to a trigger threshold  $\sim 0.10 \text{ ph cm}^{-2} \text{ s}^{-1}$ . Thus for our prototype MF,  $D(\text{Swift}) = 70 \text{ Mpc}$ . The expected rate of MF detections, given *Swift*'s sky coverage of 1.4 steradians, is then  $\dot{N}(\text{Swift}) = 53 (\tau/30 \text{ yrs})^{-1} \text{ yr}^{-1}$ , or about one MF per week. Of course, the galactic rate of MFs,  $\Gamma = \tau^{-1}$ , is very uncertain. Given that there has occurred one MF with peak luminosity in the range  $10^{47} \text{ erg s}^{-1}$  in our Galaxy during  $t_0 = 30 \text{ yrs}$  of observations, the Bayesian probability distribution for the underlying galactic rate  $\Gamma$  of such bright MFs is  $(dP/d\Gamma) = t_0 \exp\{-\Gamma t_0\}$ , with expected value  $\langle \Gamma \rangle = t_0^{-1}$ . This implies that the probability that *Swift* will detect one or more MF per month is 80%. The probability of detecting one or more event per {3, 6, 12, 24} months is {93, 96, 98, 99}%, respectively. The prospects for observing MFs during *Swift*'s 24-month prime mission are excellent.

Of course, all of the above estimates idealize MFs as “standard candles” defined by the December 27 prototype. The actual luminosity function of MFs is unknown. It is possible that some MFs are significantly brighter than the December 27 event. For example, a magnetic instability on a rare  $B_{\text{dipole}} \sim 10^{16} \text{ Gauss}$  magnetar could release  $10^{48} \text{ erg}$ , and be detected by *Swift* out to  $\sim 1 \text{ Gpc}$ . Nevertheless, we suspect that MFs constitute only a substantial subset of BATSE Class II GRBs, not all of them. For example, the 175 keV blackbody spectrum would probably result in a significantly higher hardness ratio than that of the average short-duration burst<sup>23</sup>. The fact that Class II GRBs have  $\langle V/V_{\text{max}} \rangle < 0.5$  does not seem consistent with all these events being local<sup>35</sup>. Moreover, no galaxies at  $D < 100 \text{ Mpc}$  were found for the Interplanetary Network positions of four short GRBs<sup>36</sup>.

### Studying extragalactic magnetars

*Swift* can identify MFs via their positional correlations with galaxies, allowing the source distances from Earth to be inferred. A spiral galaxy of size  $\sim 30 \text{ kpc}$  at distance  $D(\text{Swift})$  spans  $\sim 3.4 \text{ arcmin}$ , comparable to the *Swift* BAT location accuracy  $\Delta\theta_{\text{BAT}} \sim 1\text{--}4 \text{ arcmin}$ . This localization can be greatly improved, to  $< \sim 10 \text{ arcsec}$  accuracy, if the

oscillating tail of the flare is detected by *Swift*'s X-ray Telescope (XRT) when it slews to observe the burst site within about 1 minute. Our measurements of soft X-ray emissions in the giant flare tail (Figs. 4 and 5) make it possible to assess the prospects of XRT acquisition for the first time. Extrapolating our blackbody and bremsstrahlung X-ray spectral fits from our 3 keV threshold down to 0.3 keV, the December 27 pulsating tail produced a 0.3-10 keV incident fluence of  $0.18 - 1.6 \times 10^{-3} \text{ erg cm}^{-2}$ . The threshold fluence for XRT detection<sup>34</sup> is  $2 \times 10^{-10} \text{ erg cm}^{-2}$ , so the December 27 flare tail could be marginally detected to a distance of  $D_{tail} = 10 - 40 \text{ Mpc}$ . This means that at best only the nearest fraction  $[D_{tail} / D(\text{Swift})]^3 \sim 0.2$  of all MFs spotted by *Swift* will have detectable tails. We have verified that the soft X-rays are strongly pulsed (Fig. 5). For events within about 8 Mpc, simulations indicate that the magnetar's rotation period can be reliably determined. For more distant sources, the spectrum and the rapid flux decay distinguish magnetar tail emissions from cosmic GRB afterglows.

The prospects of detecting extragalactic MFs with the *Swift* Ultra-Violet and Optical Telescope (UVOT) or ground-based optical telescopes are not wholly bleak. The trapped fireball is too tiny to emit detectably in this waveband. However, one can scale directly from the observed radio afterglow (GCN Circulars), which had radio spectral index  $\alpha = -0.7$  and time decay  $t^{-1.5}$  in the optically thin regime. Extending this to a frequency of  $10^{14.5} \text{ Hz}$  gives  $L_{opt} \sim 4 \times 10^{37} t_3^{-3/2} \text{ erg s}^{-1}$  at a time  $10^3 t_3 \text{ s}$  post-flare. Such a source would have a brightness of 22<sup>nd</sup> magnitude at 1 Mpc for  $t_3 \sim 1$ .

Prospects are even better for the detection of X-ray afterglows<sup>26</sup>. SGR 1900+14 emitted strong nonthermal X-rays in the aftermath of the 1998 August 27 event<sup>47</sup>, thought to be due to a heated magnetar crust<sup>48</sup>. If this kind of afterglow scales linearly with flare energy, as found in less energetic events<sup>49</sup>, then a MF like the December 27 event would glow brighter by a factor  $f \sim 10^2$ , suggesting  $L_x \sim 2 \times 10^{39} (f/10^2) (t/1 \text{ hr})^{-0.7} \text{ erg s}^{-1}$ . This could be detected by the *Chandra X-ray Telescope* out to a distance  $D(\text{Chandra}) \sim 30 (f/10^2)^{1/2} (\Delta t_{obs}/10^4 \text{ s})^{1/2} (t/10 \text{ hr})^{-0.35} \text{ Mpc}$  in an observation of duration  $\Delta t_{obs} \ll t$  seconds.

### **New horizons and speculations**

The detection of extragalactic magnetars, if achieved by *Swift*, will open up a new field of astronomy. A catalog of giant flare spikes, once assembled, will contain a wealth of information about magnetic instabilities in neutron stars. Information about the luminosity function of MFs, their range of durations, and possible spectral diversity (suggested by measurements of the August 27 event<sup>3,30</sup>; note that less compact flows than that of the December 27 event could show nonthermal spectra) will constrain magnetar physics and population diversity. Especially interesting may be the detection of unusually bright flares from very young magnetars, with rapid rotation periods and perhaps much stronger fields than are observed in galactic SGRs. (The birthrate of SGRs is evidently so low that no stars younger than  $\sim 10^3 - 10^4$  yrs are observed in our galaxy.) MFs from very young magnetars may be disproportionately common in extragalactic studies because of their greater brightness and higher flare rate. More frequent cataclysms are expected in younger magnetars because magnetic diffusion slows down as stars age and cool.<sup>50</sup>

The nature of the instability which caused the December 27 event will be constrained by post-flare observations. Measurements of the spindown rate over the coming year will reveal whether the exterior magnetic helicity increased or decreased during the flare. SGR 1806-20 may come to resemble an Anomalous X-ray Pulsar, with diminished spindown rate and a softer X-ray spectrum. SGR 0526-66 developed these characteristics, indicating weak magnetospheric currents, after the giant flare of March 5, 1979 (ref. 13). Sporadic, short bursts were observed from SGR0525-66 until 1983<sup>6</sup>, but the source has not been observed to burst since then, suggesting that sub-crust stresses were (at least temporarily) relieved in the giant flare. We speculate that SGR 0526-66 and now SGR 1806-20 may have entered the “low” phase in a magnetar activity cycle which involves changes in the rate of expulsion of magnetic helicity out of the star.

### **Methods**

**RHESSI and Wind data analysis.** During the intense initial peak, all X- and gamma-ray detectors experienced some degree of saturation, making reliable reconstruction of the time history and energy spectrum difficult or impossible. Many small, thin silicon particle detectors, on the other hand, had very low cross-sections for X- and gamma-ray interactions, and therefore did not saturate, even though they did respond strongly to the peak. We have therefore analyzed the observations of the Wind 3D Plasma & Energetic Particle experiments<sup>17</sup> and of the RHESSI particle monitor detector<sup>18</sup> with the GEANT3 and GEANT4 simulation codes. Wind has six double-ended Solid State Telescopes (SSTs), five with two back-to-back 1.5cm<sup>2</sup>, 300 micron thick silicon detectors (called O and F), and one SST with a third, 15 cm<sup>2</sup> 500 micron thick detector (T) in between. The detectors had multi-channel analyzers covering the 20 keV – 11 MeV range with various time resolutions between 12 and 96 s, while the RHESSI detector had two discriminators with 50 and 620 keV thresholds which were read out with 0.125 s resolution. In each case, the simulations included the matter surrounding the detectors, and attempted to reproduce the observed count rates with incoming power law, thermal bremsstrahlung, and blackbody energy spectra. In all cases, the power law and bremsstrahlung spectra were strongly rejected ( $\chi^2= 42$  and 69 for TBD degrees of freedom), and only the blackbody provided an acceptable fit ( $\chi^2= 10$  for TBD degrees of freedom). These fits were performed for the Wind detectors with the highest statistics (F and O), because they gave the strongest restriction on the error bars for the blackbody temperature ( $175 \pm 25$  keV). A systematic error of  $\pm 10\%$  was assumed for these simulations. Fits including all detectors are consistent with these results.

At the time of this event, SGR1806-20 was located 5° from the solar position, outside the primary imaging field of view of the RHESSI instrument; however, a fortuitous alignment of the imaging grids allow us to get “snapshots” of the direct spectrum, down to 3 keV, twice per RHESSI rotation period (4.06 sec). We have used the on-axis RHESSI response matrices for this analysis, which should reproduce reasonable flux numbers and spectral distributions. With the current matrices we are unable to strongly distinguish between thermal bremsstrahlung and black-body spectral fits for this tail, so we have included both in this paper. We anticipate further spectral analysis including response matrices for this source location should discriminate between these models.

**Detectability by BATSE and Swift.** We estimated the BATSE sampling depth for MFs using our peak incident flux from this flare in the standard BATSE 50-300 keV energy range (determined from our best-fit RHESSI PD fluence and WIND spectral fit), over the BATSE trigger timescales of 64-ms, 256-ms, and 1024-ms. We find the optimal BATSE trigger timescale to be the 256-ms (BATSE's P256). Given the 50%-efficiency trigger flux for P256<sup>33</sup> of  $0.50 \text{ ph cm}^{-1} \text{ s}^{-1}$ , we determine that this flare would have been detected by BATSE to a distance of 31 Mpc. As a check, we analyzed the 50-300 keV fluence of all the BATSE short-hard GRBs with durations  $T_{90} = 0.1\text{-}0.2 \text{ s}$ , and found a threshold fluence of  $\sim 5 \times 10^{-8} \text{ erg cm}^{-2}$ , corresponding to comparable detection distance. This is lower than the distance originally quoted in GCN 2936<sup>38</sup> as a result of our spectral fits -- the black-body fit is much harder than typical GRB spectra, resulting in lower photon fluxes in the 50-300 keV range than a typical short-hard GRB spectrum with comparable energy flux. To estimate the Swift BAT sensitivity, we used a P256 (50-300 keV) photon flux sensitivity 5 times better than BATSE (Ref. 46, Fig. 9), corresponding to  $\sim 0.10 \text{ ph cm}^{-2} \text{ s}^{-1}$ , for a limiting detection distance for BAT of 70 Mpc. As a check, the advertised energy flux sensitivity of  $\sim 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$  yields an even larger limiting distance.

To estimate the BATSE sensitivity to pulsating tails, we examined the strongest short-hard GRB seen by BATSE, trigger #6293. This GRB had a duration  $T_{90} = 0.192 \text{ s}$ , and a total fluence of  $4.30 \times 10^{-5} \text{ erg cm}^{-2}$ , dominated by photons  $> 300 \text{ keV}$ . Given the background count rate in the 400-s period after this burst, we estimate a  $5\sigma$  upper limit on a 20-100 keV tail fluence of  $2 \times 10^{-7} \text{ erg cm}^{-2}$ , setting the BATSE upper limit on the ratio of tail-to-peak fluence of 0.5%.

To estimate the Swift XRT sensitivity to the pulsating tails, we used the XRT response available in the HEASARC WebPIMMS package. We developed a model of the pulsating X-ray tail from our time-dependent thermal bremsstrahlung fits over the course of the 380-s tail, assuming the average 3-10 keV pulse shape. Folding the time-dependent model through the XRT response, and assuming an optimistic 20-s slew time, we estimate a marginal 0.3-10 keV detection of the soft tail at 10 - 40 Mpc for blackbody and bremsstrahlung spectra. As a check, the December 27 tail produced an incident 0.3-10 keV fluence of  $0.18 - 1.6 \times 10^{-3} \text{ erg cm}^{-2}$ . The quoted threshold flux for XRT detection is  $2 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$  for a  $10^4 \text{ s}$

observation, corresponding to a fluence threshold of  $2 \times 10^{-10}$  erg cm<sup>-2</sup>. Comparing this with our measured X-ray fluence yields a comparable detection distance. We also determined that the magnetar rotation period can be picked out of the XRT data by FFTs out to distances of  $\sim 2 - 8.5$  Mpc (it is clearly seen by eye out to  $\sim 1 - 4$  Mpc).

**Rate of magnetar flares.** To estimate the rate of extragalactic magnetar flares, we needed to estimate the blue luminosity of the Milky Way,  $L_B(MW)$ . The synthetic Galactic model of ref. 44, based upon *Hipparcos* data and recent large-scale surveys in the optical and infrared, implies a Galactic mass  $M(MW) = 2 \times 10^{10} M_{Sun}$ . We divided this by  $M / L_B = 1.4 M_{Sun} / L_{Sun}$  which was found from the average of 30 MW-like galaxies of types Sb-Sc with luminosities  $5 \times 10^9 - 5 \times 10^{10} L_{Sun}$  within the Nearby Field Galaxy Survey (Sheila Kannappan, private communication).

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We are grateful to John Scalo, Ethan Vishniac, and Sheila Kannappan for discussions and expert help. In the US, this work was supported by NASA. The INTEGRAL mission is supported by the German government via the DLR agency. The authors declare that they have no competing interests.

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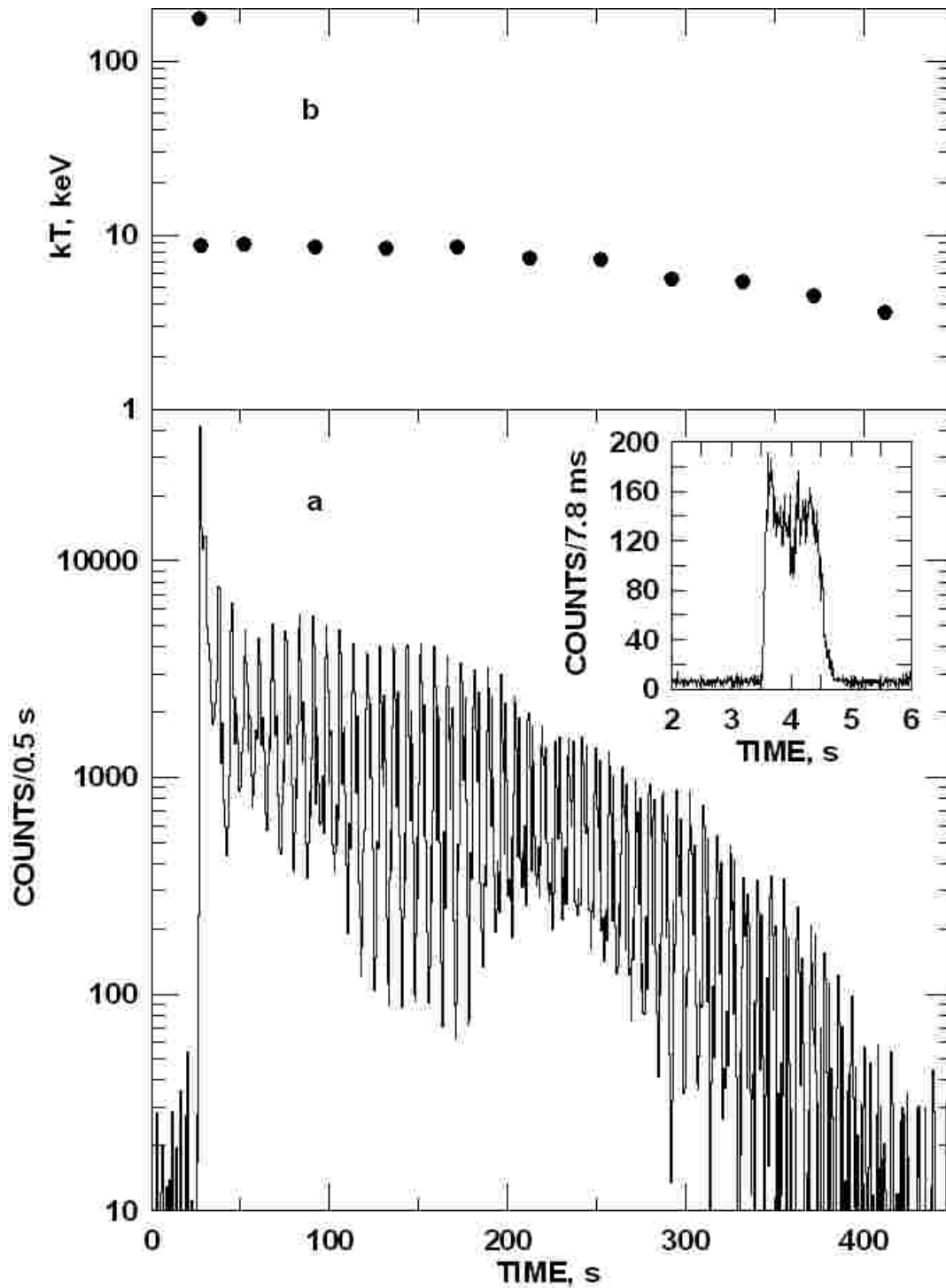


Figure 1. RHESSI germanium detector data for the 27 December 2004 giant flare. **a.** 20-100 keV time history plotted with 0.5 s resolution. Zero seconds corresponds to 77400 s UT. In this plot the flare commenced at 26.64 s and

saturated the detectors within 1 ms . The detectors emerged from saturation on the falling edge 200 ms later and remained unsaturated after that. The amplitude variations in the oscillatory phase appear to be real, and are not caused by any known instrumental effect. Inset: time history of the precursor with 8 ms resolution. Zero corresponds to 77280 s UT. **b.** Spectral temperature vs. time in the oscillatory phase. Although RHESSI measured time- and energy-tagged photons continuously, 'clean' spectra (that is, unabsorbed by intervening materials) were measured for short intervals only twice each 4.06 s spacecraft spin period during the oscillatory phase. Preliminary spectral analysis (3-100 keV), using the RHESSI on-axis response matrices, are generally consistent with a single temperature blackbody or optically thin thermal bremsstrahlung model; the blackbody temperatures have been plotted. The formal uncertainties are smaller than the data points and are not shown.

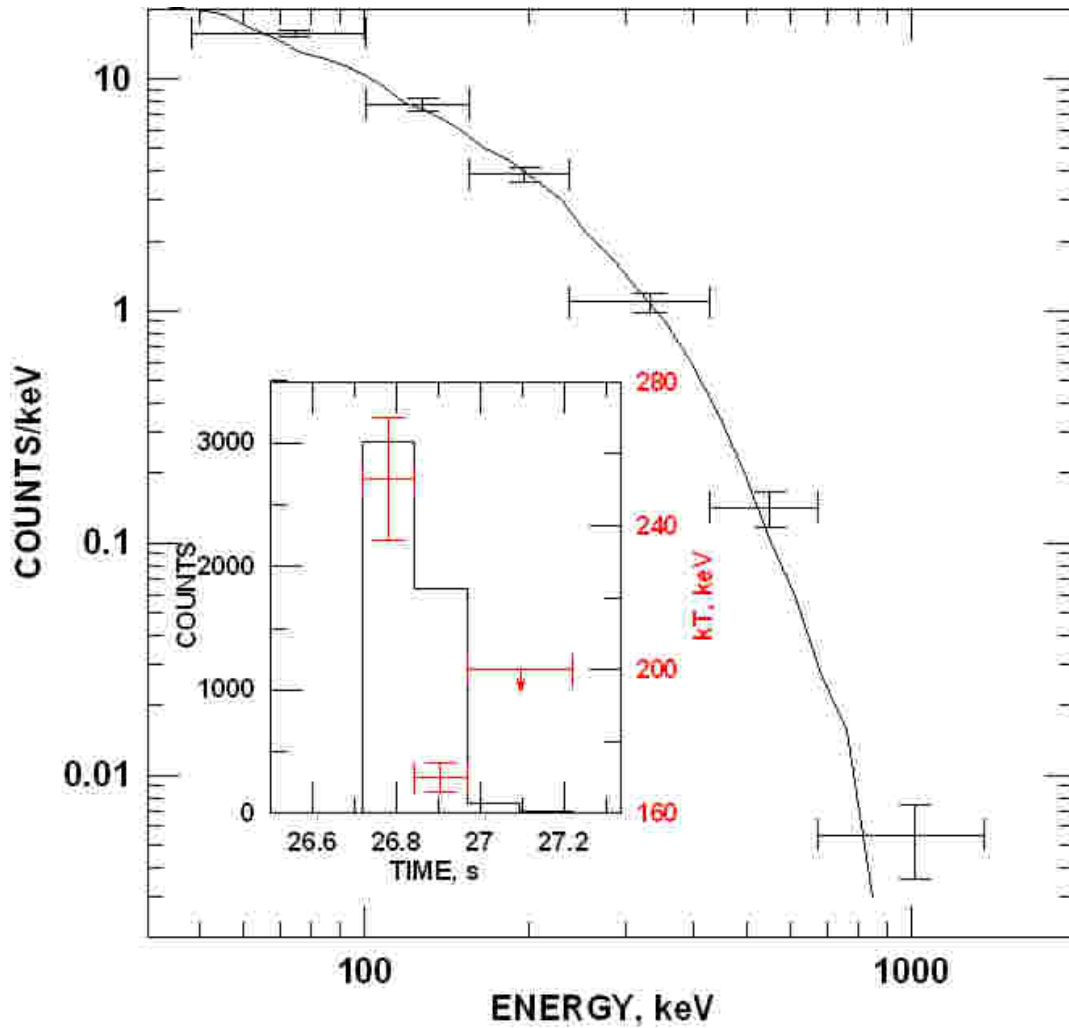


Figure 2. Spectrum and time history of the initial peak. The error bars show the spectrum measured by the Wind 3D O detector<sup>17</sup> with coarse time resolution which averages over the peak. The line is the best fitting blackbody convolved with the detector response function; its temperature is  $175 \pm 25$  keV. Inset: The time history of the peak (black, left-hand scale) and of the blackbody temperature (red, right-hand scale) with 0.125 s resolution, from the RHESSI particle detector<sup>18</sup>.

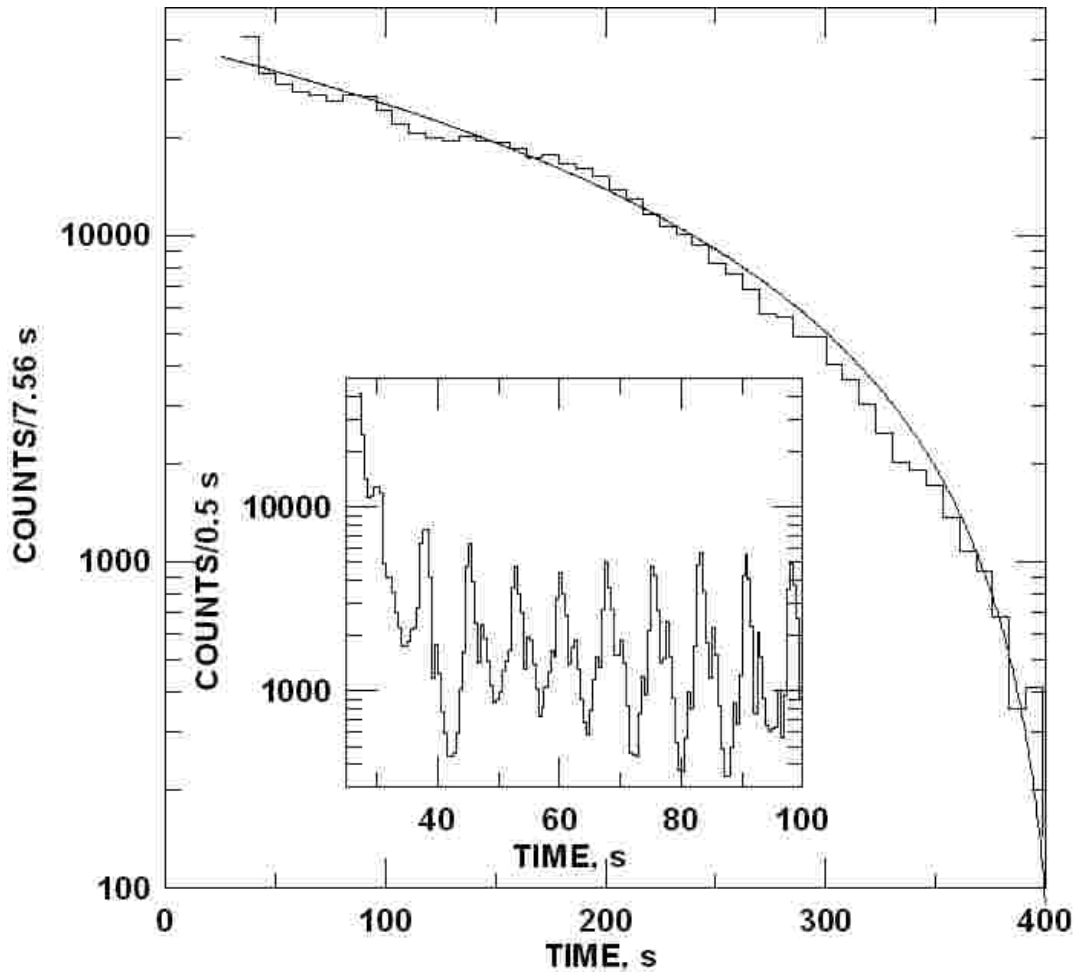


Figure 3. Step plot: counts in the oscillatory phase of the giant flare, averaged over the 7.56 s rotation period of the neutron star. The smooth line corresponds to a fit using the evaporating fireball model<sup>16</sup>. Zero corresponds to 77280 s UT. Inset: RHESSI germanium detector light curve for the first 10 cycles of the flare tail. The first peak of the trapped fireball emission is evident on the falling edge of the hard spike at  $t = 30$  s. A two-peaked pulse-interpulse structure is present even in this early phase of tail development.

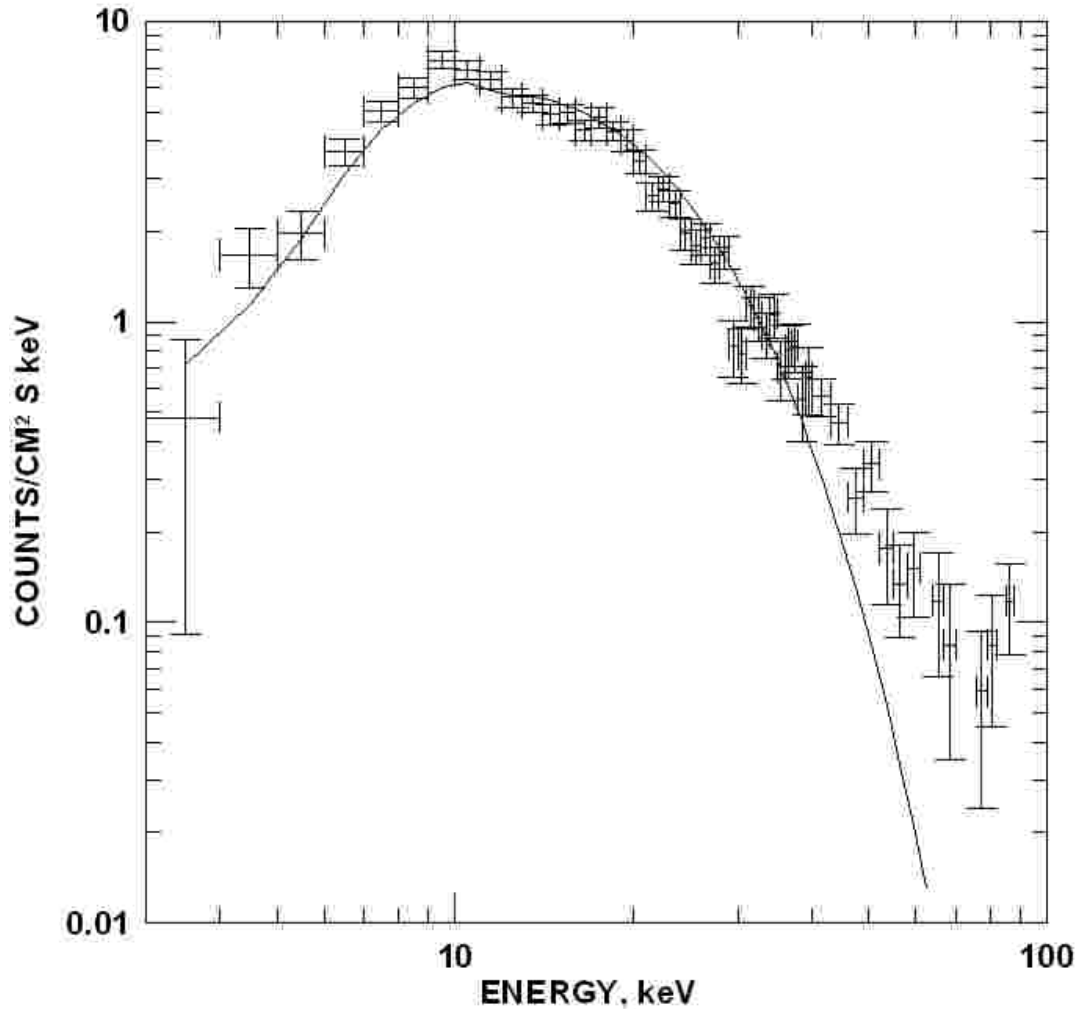


Figure 4. 3-100 keV phase-averaged energy spectrum of the pulsed tail. The error bars show the measured spectrum; the solid line represents a fit to a blackbody function  $E^2 (\exp(E/kT)-1)^{-1}$ , where  $E$  is the energy and  $kT=5.1 \pm 1.0$  keV. This spectrum is averaged over various phases between 272 and 400 s in Figure 1, corresponding to intervals where the photons could reach the detectors passing through a minimum amount of intervening materials. An optically thin thermal bremsstrahlung function with  $kT \sim 22$  keV provides a reasonable fit. The spectra show evidence of deviations from both models, but

it is too early to determine whether these will remain when a more refined response matrix is utilized.

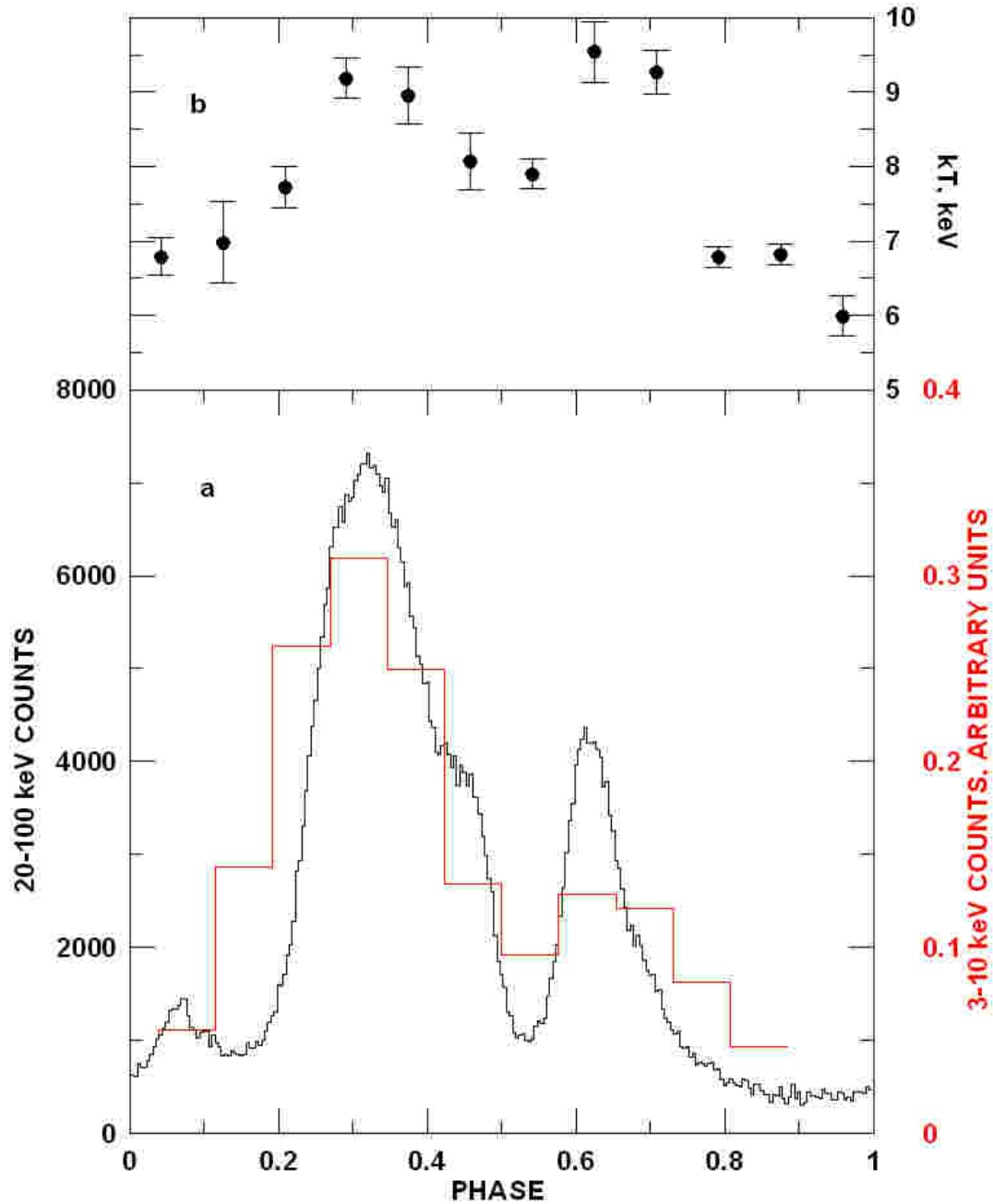


Figure 5. a. RHESSI light curve for the oscillatory portion of the giant flare, folded modulo the 7.56 s neutron star rotation period (20-100 keV, black curve, and 3-10 keV, red curve). b. The blackbody spectral temperature  $kT$ .

