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DISCOVERY OF A NEW SOFT GAMMA REPEATER: SGR J0418 + 5729

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ABSTRACT

On 2009 June 5, the Gamma-ray Burst Monitor (GBM) onboard the *Fermi* Gamma-ray Space Telescope triggered on two short, and relatively dim bursts with spectral properties similar to Soft Gamma Repeater (SGR) bursts. Independent localizations of the bursts by triangulation with the *Konus-RF* and with the *Swift* satellite, confirmed their origin from the same, previously unknown, source. The subsequent discovery of X-ray pulsations with the Rossi X-ray Timing Explorer (*RXTE*), confirmed the magnetar nature of the new source, SGR J0418 + 5729. We describe here the *Fermi*/GBM observations, the discovery and the localization of this new SGR, and our infrared and *Chandra* X-ray observations. We also present a detailed temporal and spectral study of the two GBM bursts. SGR J0418 + 5729 is the second source discovered in the same region of the sky in the last year, the other one being SGR J0501 + 4516. Both sources lie in the direction of the galactic anti-center and presumably at the nearby distance of ~ 2 kpc (assuming they reside in the Perseus arm of our galaxy). The near-threshold GBM detection of bursts from SGR J0418 + 5729 suggests that there may be more such "dim" SGRs throughout our galaxy, possibly exceeding the population of "bright" SGRs. Finally, using sample statistics, we conclude that the implications of the new SGR discovery on the number of observable active magnetars in our galaxy at any given time is $\lesssim 10$, in agreement with our earlier estimates.

Subject headings: pulsars: individual (SGR J0418 + 5729) − stars: neutron − X-rays: bursts

1. INTRODUCTION

In the last decade, observational evidence for neutron stars with extreme surface dipole magnetic fields (B$\sim 10^{14} - 10^{15}$ G) or "magnetars" has steadily grown; to date, we have more than 15 magnetar candidates. The majority of magnetars are members of two neutron star populations historically known as Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs); a couple were previously classified as Isolated Neutron Stars or Compact Central Objects. Although these systems have tangible differences, they are also linked with a multitude of similar properties, such as: (*i*) relatively long spin periods (2−12 s), (*ii*) large spin-down torques, (*iii*) low galactic latitudes, (*iv*) multiple, very intense ($10^{37} \lesssim L \lesssim 10^{41}$ erg/s), and short (duration ~ 0.1 s) bursts of hard X-/soft gamma rays – with rare occasions of Giant Flares (GFs) that are extremely energetic (with peak luminosities $\gtrsim 10^{45}$ erg/s). Most sources are visible only in X- and low-energy gamma rays; very few have been also detected in the optical and infra-red, while two sources have been observed at radio wavelengths (Camilo et al. 2006, 2007). All but two reside in our Milky Way.

The magnetar population has increased very slowly since the discovery of the first SGR source in 1986 (Atteia et al. 1987; Laros et al. 1987) and the confirmation, through bursting episodes, that AXPs were part of the same group in 2002 (Gavriil et al. 2002). New members are added in the group when (i) they are detected to emit multiple, soft short bursts and (ii) a spin period is found and a spindown rate is measured, which lead to magnetar like $B-$field estimates. During the 9 years of operation of the Compton Gamma Ray Observatory (CGRO; 1991-2000), we discovered only one new

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SGR source, SGR 1627−41 (Kouveliotou et al. 1998). In the first ∼4 years of operation of NASA's *Swift* Gamma Ray Burst (GRB) satellite, no new source was discovered, although there were several outbursts from known SGRs recorded during that period, notably the Giant Flare from SGR 1806 − 20 (Palmer et al. 2005), and active episodes from SGRs 1900 + 14 and 1627 − 41 (Israel et al. 2008; Esposito et al. 2008). The *Fermi* Observatory was successfully launched on 2008, June 11 and the *Fermi*/Gamma-ray Burst Monitor (GBM) began normal operations on July 14, when the trigger algorithms were enabled. During the first 16 months of operation we recorded emission from four SGR sources. Of these sources, only one was a known magnetar: SGR 1806 − 20. The other three detections were two brand new sources, SGR J0501 + 4516, discovered with *Swift* and extensively monitored with both *Swift* and GBM; SGR J0418 + 5729, discovered with GBM, Swift and *Konus-RF*; and SGR J1550 − 5418, a source originally classified as an Anomalous X-ray Pulsar (AXP 1E1547.0 − 5408) by Camilo et al. (2007).

We present here the discovery of SGR J0418 + 5729 together with an analysis of the bursts detected from this source with the *Fermi*/GBM. In §2, we briefly describe the source discovery and its localization by triangulation. We present the results of the precise source localization with the *Chandra* X-ray Observatory and our infrared observations in §3. In section §4 we describe the properties of the GBM bursts and the results of our search for additional untriggered events in the GBM data. Finally we discuss the implications of our discovery in §5.

2. *FERMI*/GBM OBSERVATIONS AND LOCALIZATION BY TRIANGULATION

The *Fermi*/GBM consists of 12 NaI detectors (8−1000 keV) arranged in 4 clusters of three each and 2 BGO (0.20−40 MeV) detectors at opposite sides of the spacecraft (for a detailed description of the instrument, see Meegan et al. 2009). GBM is currently the only gamma-ray instrument with continuous broad-band energy coverage (8 keV−40 MeV) and a wide field of view (8 sr; un-occulted) and is, therefore, uniquely positioned to accomplish a comprehensive magnetar (or any transient event) monitoring. In trigger mode, GBM provides three types of data: CTIME Burst, CSPEC Burst, and Time Tagged Event (TTE) data (Meegan et al. 2009). The TTE data provide time-tagged photon event lists for an accumulation time of ∼330 s, starting ∼30 s prior to the trigger time; this data type provides a superior temporal resolution down to 2μs at the same spectral resolution as the CSPEC Burst data.

GBM triggered on two SGR-like bursts on 2009 June 5 at 20:40:48.883 UT and 21:01:35.059 UT (van der Horst et al. 2009). Their final on-ground calculated locations, RA, Dec (J2000) = 70.0, +55.6 ($4^{\rm h}40^{\rm m}$, $+55°35'$) and 60.5, +55.4 ($4^{\rm h}02^{\rm m}$, $+55°22'$), are shown in Figure 1 (top panels) as asterisks with 1, 2, and 3σ statistical uncertainty contours. The positions are consistent at the 1σ level with a common origin, and inconsistent at the 3σ confidence level with the known nearby SGR source, SGR J0501 + 4516, discovered with *Swift* in August 2008 (shown in the Figure 1 top panels as a cross). For both triggers, however, there is a systematic component to the localization uncertainty of 2 − 3° so that a reactivation of this known SGR could not initially be excluded, and indeed appeared the most likely origin for these events.

The first GBM burst was seen also by the gamma-ray spectrometer, *Konus-RF*, onboard the CORONAS-PHOTON spacecraft and by the *Swift*/Burst Alert Telescope (BAT), which was triggered in its partially coded field-of-view. The second GBM burst was seen weakly in, but did not trigger, the BAT. Triangulation annuli of the GBM-*Konus-RF* and the GBM-BAT light curves for the first trigger are shown in Figure 1 (right upper panel); the GBM localizations and 1σ contours are also displayed. Subsequent ground analysis of the BAT data revealed a weak source at RA, Dec (J2000) = 64.606, +57.489 ($4^{\rm h}18^{\rm m}25^{\rm s}$, $+57°29'16''$) with an uncertainty of 4′. The GBM localizations for both events are consistent with the BAT position for the source, shown as a cross in Figure 1 (right upper panel). The annuli clearly exclude the position of SGR J0501 + 4516; the distance between the two sources is ∼ 12°. Given these results we concluded that GBM detected SGR-like emission from a new source, which we named SGR J0418 + 5729 (van der Horst et al. 2009).

3. PRECISE SOURCE LOCATION WITH *SWIFT*, *CHANDRA* AND INFRARED OBSERVATIONS

The *Swift*/X-Ray Telescope (XRT) observed SGR J0418 + 5729 starting at 2009 July 8 at 20:52:35 UT (when the source came out of Sun constraints for *Swift*) in photon counting mode for a total exposure time of 2.95 ks. A new X-ray source was found at $RA = 04^{\rm h}18^{\rm m}33.70^{\rm s}$, $Dec = +57°32'23.7''$ (J 2000) with an error circle radius of 3.6″. The XRT location is shown in Figure 1 (bottom panel) and is ∼ 3.3′ away from the initial *Swift*/BAT location.

To obtain a precise location of the source, we observed the field containing SGR J0418 + 5729 with the *Chandra*/High Resolution Camera (HRC) in imaging mode for 23.8 ks on 2009 July 12 (Observation ID 10168; ToO Observations of SGRs, PI: C.Kouveliotou). We constructed a binned (by a factor of two) image in the 0.5−7 keV band of the entire HRC-I field and searched for point sources at 5σ above the background level. We discovered three previously uncatalogued X-ray sources. We searched and detected coherent pulsations at the spin period (9.08 s, Göğüş et al. 2009a) of SGR J0418 + 5729 in the X-ray flux of the brightest X-ray source, which we identified as the X-ray counterpart of SGR J0418 + 5729 (Woods et al. 2009). The precise location (absolute positional uncertainty of 0.35″ at the 95% confidence level) of the source is shown in Figure 1 (lower panel) and also given in Table 1 together with the coordinates of the other two sources.

The *Chandra* position of SGR J0418 + 5729 was observed with the Wide field Infrared Camera (WIRC, Wilson et al. 2003) on the 5m Palomar Hale telescope on 2009 August 2 (Wachter et al. 2009). WIRC has a field of view of 8.7′ × 8.7′ and a pixel scale of 0.2487″/pixel. We obtained 26 $K_{\rm s}$ band images using two 13-position dither scripts (the second script spatially off-set from the first) - each position was a co-added exposure of twelve 5 s images. Atmospheric conditions were very good with seeing < 1″ and clear skies during observations.

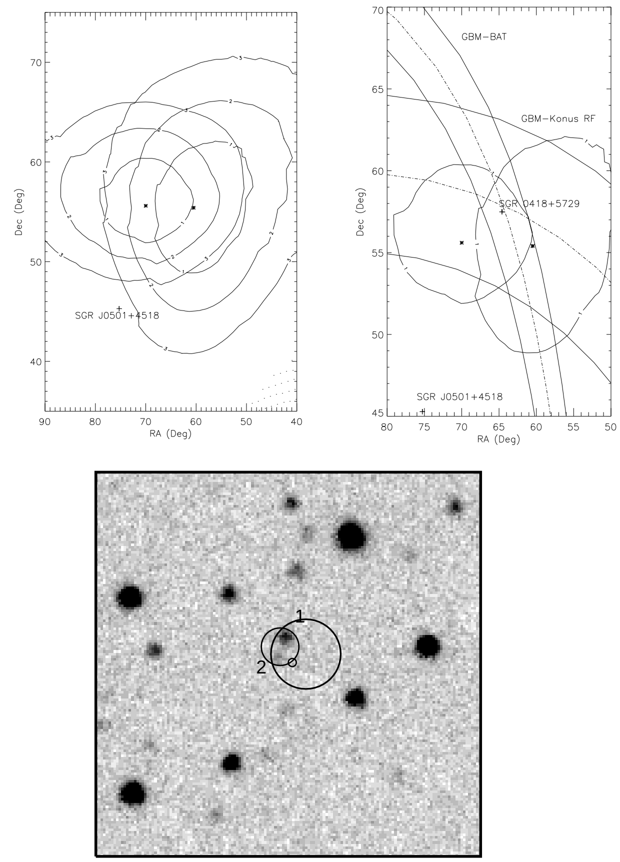

FIG. 1.— *Top Left:* GBM localizations (asterisks) for the two SGR J0418 + 5729 triggers on 2009 June 5. The contours indicate 1, 2, and 3σ statistical uncertainties. The position of the known SGR J0501 + 4516 is also shown. It is marginally consistent with the GBM events if one takes into account an additional $2-3°$ systematic component to the localization uncertainties. *Top Right:* Triangulation annuli (90% confidence level) for the first SGR J0418 + 5729 trigger seen by GBM, *Konus-RF* and *Swift*/BAT on 2009 June 5. The asterisks and contours show the 1σ (statistical uncertainty) localization of both GBM triggers (also shown in top left panel). A cross marks the position of the source, found in ground analysis using the *Swift*/BAT data (with a 4′ uncertainty at 90% confidence level). *Bottom:* A $37'' \times 37''$ $K_{\rm s}$ band image of the field of SGR J0418 + 5729 obtained with Palomar/WIRC. North is up and east to the left. Our *Chandra*/HRC error circle with radius 0.35″ is shown, as well as the original (3.6″, Göğüş et al. 2009b) and refined (1.9″, Cummings et al. 2009) error circles obtained with *Swift*/XRT. Photometry of the sources closest to the *Chandra*/HRC position results in $K_{\rm s} = 17.66 \pm 0.04$ for source 1 and $K_{\rm s} = 18.8 \pm 0.1$ for source 2.

The individual frames were reduced using a suite of IRAF scripts and FORTRAN programs. These scripts first linearize and dark-subtract the images. A sky frame and flat field image are created from the list of input images, and subtracted from and divided into (respectively) each input image. At this stage, WIRC images still contain a significant bias that is not removed by the flat field. Comparison of 2MASS and WIRC photometric differences across the array shows that this flux bias has a level of ∼10% and the pattern is roughly the same for all filters. Using these 2MASS-WIRC differences for many fields, one can create a flux bias correction image that can be applied to each of the "reduced" images. Finally, we astrometrically calibrated the images using 2MASS stars in the field. The images were then mosaicked together and the mosaic was photometrically calibrated using 2MASS stars. Magnitudes were computed using the IRAF phot routine with the zero points as found using the 2MASS stars. The final image (see bottom panel of Figure 1) has a 5σ $K_{\rm s}$ detection limit of 21.6 mag.

The astrometric solution was derived based on 90 2MASS source matches and carries a formal 1σ error of 0.1″ for the transfer of the 2MASS reference frame to the WIRC image (in addition to the intrinsic 0.1″ 1σ uncertainty of the 2MASS reference system). The two additional X-ray sources (see Table 1) have unambiguous IR counterparts in our WIRC image and hence can be used to tie the X-ray astrometry to that of the IR 2MASS system. We find a small systematic offset between the two reference systems of 0.33″ in *RA* based on those two sources and no systematic difference in *Dec*. The X-ray positions in Table 1 have been corrected for this shift and are thus registered to the 2MASS astrometric reference frame.

TABLE 1
Chandra/HRC COORDINATES OF SGR J0418 + 5729 AND THE TWO X-RAY SOURCES WITH IR COUNTERPARTS

Source	Right Ascension	Declination
SGR J0418 + 5729	$04^{\rm h}18^{\rm m}33^{\rm s}.867$	$+57°32'22.91''$ (J2000)
CXOU J041819.0+573341	$04^{\rm h}18^{\rm m}19^{\rm s}.097$	$+57°33'41.75''$ (J2000)
CXOU J041812.5+573154	$04^{\rm h}18^{\rm m}12^{\rm s}.578$	$+57°31'54.99''$ (J2000)

Our $K_{\rm s}$ band image overlaid with the X-ray error circles of Göğüş et al. (2009b), the refined *Swift*/XRT position by Cummings et al. (2009) and our *Chandra* position is shown in Figure 1 (bottom panel). No obvious IR counterpart is detected inside the *Chandra*/HRC error circle. Two sources (labelled 1 and 2 in the Figure 1 bottom panel) with $K_{\rm s} = 18.8 \pm 0.1$ and $K_{\rm s} = 17.66 \pm 0.04$ are detected within the refined *Swift* error circle of Cummings et al. (2009). However, our *Chandra*/HRC position is sufficiently offset from this *Swift*/XRT position to exclude both of these sources. Possibly, a third, very faint source is seen at the southwestern edge of the *Chandra*/HRC error circle. Unfortunately, this source is at the detection limit with $K_{\rm s} = 21.6 \pm 1.3$ and cannot be reliably distinguished from a noise spike in the background. Hence our IR observations fail to reveal a convincing counterpart candidate for SGR J0418 + 5729.

4. SGR J0418 + 5729 BURST ANALYSIS

We have searched the daily GBM continuous data files for untriggered bursts from SGR J0418 + 5729 starting two days before the two triggered events and ending six days after; our total search duration thus covered 2009 June 3−11. We used the combined CTIME data type (in continuous mode with 256 ms time resolution and in Burst mode with 64 ms resolution when there was a trigger), with 8-channel spectral resolution. Our search algorithm filters count rates between 10−300 keV for all 12 detectors and identifies events that are seen in at least two detectors, in excess of at least 5.5σ and 4.5σ above background level in the first and second brightest detectors, respectively. For each event identified by our burst search algorithm, we subsequently (i)

investigated energy-resolved burst morphology and (*ii*) compared detector zenith angles to the source for all 12 detectors to confirm that the burst originated from SGR J0418 + 5729.

Our search identified only three events from SGR J0418 + 5729, all detected on 2009 June 5: these include one untriggered burst at 20:35:54.703 UT, and the two triggered events from the source. The untriggered event took place ~ 5 min before the first GBM trigger and is relatively weak and soft. It was detected only at energies $\lesssim 50$ keV, and its location is consistent at the 1σ level with the SGR J0418 + 5729 location. We also checked the *Swift*/BAT data and although the source was in the BAT field-of-view, we did not see a rate increase at the event time. No other untriggered bursts were found during the 8-day span of the search.

Additionally, a search through $\gtrsim 4000$ IPN events with fluences $\gtrsim 7\times10^{-6}$ erg cm^{-2} and/or peak fluxes > 1 photon cm^{-2} s^{-1} in the $25 - 150$ keV energy range, going back to 1990, does not reveal a significant excess of bursts in the direction of SGR J0418 + 5729. We conclude that the source did not undergo any episode of intense activity during this time, although we cannot exclude the possibility of isolated, weak events similar to the ones reported in this paper.

We have performed detailed temporal and spectral analysis on the two triggered events using the TTE data type. For the third (untriggered) event only continuous CTIME and CSPEC data are available, with 256 ms and 4096 ms resolution, respectively. This weak event is not significantly detected above background in the continuous CSPEC data due to the coarse time resolution, but is detected as 1 time bin in the continuous CTIME data. Since the CTIME data spectral resolution is relatively coarse (only 8 channels), we did not perform a detailed spectral analysis for this event.

The TTE data of the two triggered events were analyzed with the *RMFIT (3.2rc2)* spectral analysis software developed for the GBM data analysis[19]. We generated Detector Response Matrices using *GBM_RSP_Gen v1.81*. For both events we used in our analysis the three NaI-detectors with the smallest zenith angles to the source, i.e. NaIs 3, 4 and 5. The zenith angles for these detectors range from 26° to 44°. The T_{90} and T_{50} event durations were estimated in *RMFIT* by constructing cumulative fluence plots over the energy range $8 - 200$ keV for the three detectors combined, and then determining the times during which 90% and 50% of the burst counts were accumulated (Kouveliotou et al. 1993). For the first trigger we find $T_{90}(T_{50}) = 40 \pm 7$ ms (10±4ms), and for the second trigger $T_{90}(T_{50}) = 80 \pm 6$ ms (34±4 ms).

Figure 2 shows the light curve in the detector with the smallest zenith angle for both events, with the intervals used for the spectral analysis indicated. Note that these intervals are somewhat larger than the T_{90} durations of the bursts, to encompass their full emission period for the spectral analysis. We have fitted the time-integrated spectra with various functions: power law, cut-off power law, black body, and optically-thin thermal bremsstrahlung (OTTB). We find that OTTB

[19] R.S. Mallozzi, R.D. Preece, & M.S. Briggs, "RMFIT, A Lightcurve and Spectral Analysis Tool," ©2008 Robert D. Preece, University of Alabama in Huntsville, 2008

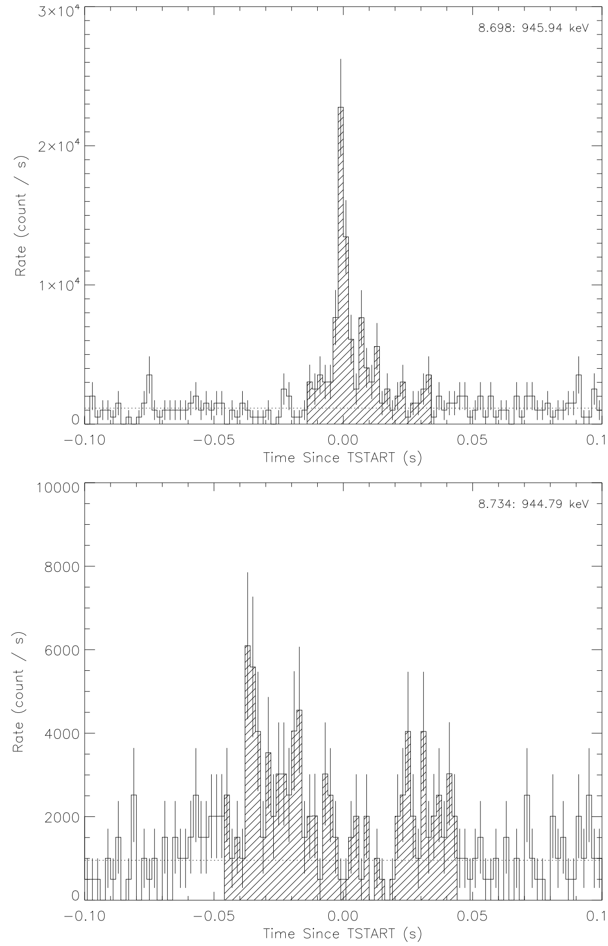

FIG. 2.— TTE light curves of the two SGR J0418 + 5729 triggered events. The hatched areas indicate the time intervals used for spectral analysis.

provides the best fits in both cases (Table 2) similar to what has been found for other SGR bursts (Göğüş et al. 1999, 2000). The cut-off power law gives a better statistics value (Table 2), which is not statistically significant given that this model has 1 additional free parameter compared to OTTB. The best-fit count spectra are shown in Figure 3. From the Figure and the fit parameters, it is clear that the spectrum becomes softer from the first to the second burst.

To estimate the total energy output of the bursts, we need to know the distance to the source. SGR J0418 + 5729 is located in the galactic plane and in the galactic anti-center direction. The biggest concentration of stars in that direction is in the Perseus arm of our galaxy, at a distance of 1.95 ± 0.04 kpc (Xu et al. 2006). We provide here the SGR J0418 + 5729 burst energetics, assuming that the source is located in the Perseus arm, which we consider as an upper limit of the energetics. Adopting this distance implies energies of $\sim 4 \times 10^{37}$ and $\sim 2 \times 10^{37}$ erg for the two bursts respectively, which is at the lower end of the distribution compared to other SGR bursts (Göğüş et al. 1999, 2000). We note that an OTTB fit to the CTIME continuous data of the third (untriggered) event, implies an energy of $\sim 8 \times 10^{36}$ erg, albeit with very low statistics.

TABLE 2
Spectral analysis results of the SGR J0418 + 5729 bursts

Time	OTTB		Cut-off Power Law			Energy Flux
	kT	cstat/dof	Index	$E_{\rm peak}$	cstat/dof	(8−200 keV)
(UT)	(keV)			(keV)		(10^{-6} erg/cm^2/s)
20:40:48.869 − 20:40:48.917	33.46 ± 2.23	296.76/361	-0.51 ± 0.26	34.72 ± 1.85	294.85/360	2.00 ± 0.08
21:01:35.013 − 20:40:35.103	19.71 ± 1.96	335.15/361	-0.66 ± 0.52	21.39 ± 2.55	334.85/360	0.60 ± 0.04

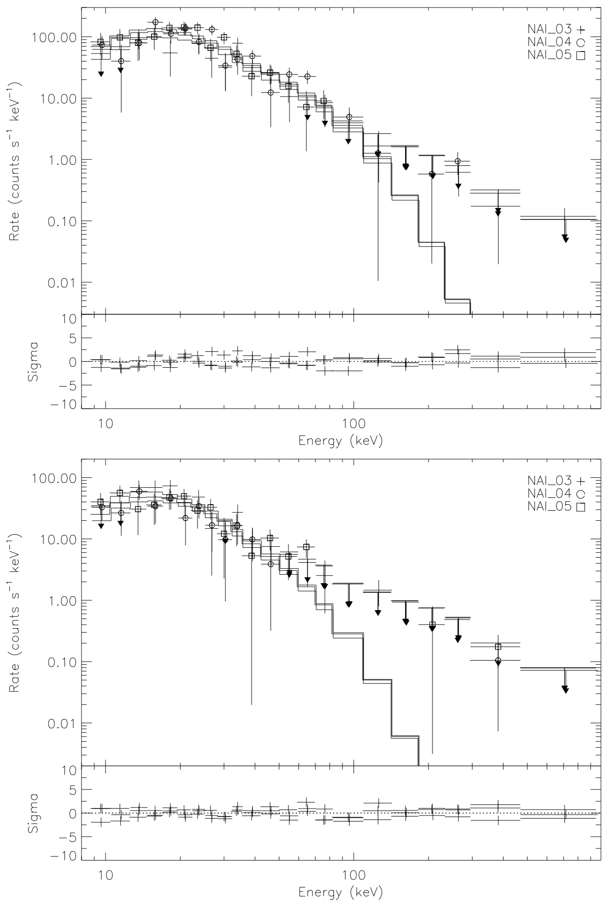

Fig. 3.— Best fit OTTB count spectra of the two SGR J0418 + 5729 triggered events.

5. DISCUSSION

During the first year of operations of the *Fermi*/GBM, we have detected bursts from four SGRs, of which two were already known sources and two were newly detected ones. SGR J0418 + 5729, in particular, was discovered with GBM and located by triangulation with *Konus-RF* and *Swift*. The source was subsequently confirmed as a magnetar candidate with the Rossi X-ray Timing Explorer (*RXTE*) observations (Göğüş et al. 2009a), which revealed a spin period of 9.0783±0.0001 sec in the persistent X-ray emission of the source. Although the source lies in the direction of the galactic anti-center and presumably at the nearby distance of ~ 2 kpc (assuming it resides in the Perseus arm of our galaxy), it was not detected at any other wavelength (IR, optical and radio). Interestingly, this is the second source discovered in the same region of the sky (including SGR J0501 + 4516) in one year. The X-ray properties of the source's persistent emission will be described elsewhere (Woods et al., in preparation).

The scarcity of magnetars contributes to the many open questions related to their nature, in particular the true number density and birth rate of these objects. The latest two new SGRs from roughly the same direction, if indeed at the relatively small distance of $\sim$2 kpc, suggest that there are more such "dim" SGRs throughout our galaxy, undetectable unless they are relatively close to us. Indeed the trigger detection threshold of the two GBM triggers from SGR J0418 + 5729 indicates that if their origin was ~ 1.5 times further away, namely at $\sim$3 kpc, we would not have detected them. This raises the question: what is the population of such "dim" SGRs? A very rough estimate comparing 2 SGRs at $\sim$2 kpc versus 4 at $\sim$10 kpc, and assuming a uniform distribution within the Galactic plane, gives $\sim 10-15$ times more "dim" sources active at a given time. To dominate the magnetar birth rate their active lifetimes should not be larger by more than this factor compared to those of "bright" SGRs.

We have estimated the size of the parent population of SGRs using a technique that is commonly employed in the fields of biology and ecology to estimate animal populations (Seber 1982). This ("Mark and Recapture") technique is based on capturing and marking a random sample of animals, and then returning them to the population and allowing them to remix. When a new sample is captured later, the fraction of the recaptured animals that were already marked, and hence are in both samples, can be used to estimate the population size. We applied this technique (Seber 1982) to the SGR observations assuming that the SGR population has (i) fixed membership, and (ii) is homogeneous in its bursting characteristics. There are several caveats associated with these assumptions (e.g., if some SGRs are quiescent for many decades, and then start bursting again, then the sample is biased towards a false "new" source), but we are using this estimate as a first order approximation. For the initial sample, we used the number of SGRs (5) found by all instruments in the thirty years prior to GBM (note, that there was not always a complete sky coverage during this period and at times there were several large gaps, when no instrument was available to confirm SGR activity). The GBM observations have resampled the SGR population, finding 4 SGRs, 2 old and 2 new. The unbiased form of the Lincoln-Petersen equation (Seber 1982) estimates that the size of the SGR population is 9 $(+17.3/-1.6)$. The interpretation is that GBM is finding 50% old and 50% new SGRs, suggesting that the previously known sample is about half of the population observable by GBM.

The discovery of SGR J0418 + 5729 adds a seventh confirmed member in the SGR subgroup of magnetars in the last 30 years. Together with the known

AXPs, the total tally is ~ 15 sources, a very restricted membership club. Given their small numbers, previous magnetar rate estimates (Kouveliotou et al. 1994; Gaensler et al. 1999; Gill et al. 2007; Leahy et al. 2007) concluded that roughly 10% of neutron stars become magnetars. Our current rate estimates (based on the currently detectable sources) are consistent with the above, and with our earlier suggestion (Kouveliotou et al. 1994) that our galaxy contains at any given time a few active magnetar sources. However, if a dim, largely undetected as yet magnetar population exists, as the GBM detection of SGR $\mathrm{J}0418+5729$ indicates, it might significantly contribute to and increase the magnetar birth rate.

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