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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* 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 number of observable active magnetars in our Galaxy at any given time is $\lesssim$10, in agreement with our earlier estimates.

Key words: 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" (Duncan & Thompson 1992) has steadily grown, with more than 15 magnetar candidates to date. 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 (for recent reviews, see Woods & Thompson 2006; Mereghetti 2008). Most sources are visible only in X- and low-energy gamma rays; very few have also been detected in the optical and infrared, 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 in 1979 of sources of repeated soft gamma-ray bursts (Mazets et al. 1979b, 1979a; Golenetskii et al. 1984; Laros et al. 1986, 1987), later associated with a new class of astrophysical objects named SGRs (Atteia et al. 1987; Laros et al. 1987; Kouveliotou 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 (1) they are detected to emit multiple, soft short bursts and (2) a spin period is found and a spindown rate is measured, which lead to magnetar-like B-field estimates. During the nine years of operation of the *Compton Gamma Ray Observatory* (*CGRO*; 1991–2000), we discovered only one new SGR source, SGR 1627−41 (Kouveliotou et al. 1998). In the first ~4 years of operation of the *Swift* satellite, no new source was discovered, although several outbursts from known SGRs were recorded

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(Palmer et al. 2005; 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. During the first 17 months of operation, we recorded emission from four SGR sources, of which 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 known as AXP 1E1547.0−5408 or PSR J1550−5418 (Camilo et al. 2007).

We present here the discovery of SGR J0418+5729 and its localization by triangulation in Section 2, and the precise source localization with the *Chandra* X-ray Observatory and our infrared observations in Section 3. In Section 4, we describe the properties of the GBM bursts, and in Section 5 we discuss the implications of our discovery.

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

The *Fermi*/GBM has a wide field of view (8 sr) with broadband energy coverage (8 keV–40 MeV) and is, therefore, uniquely positioned to detect transient events (for a detailed description, see Meegan et al. 2009). When GBM is triggered, three types of data are accumulated: CTIME burst, CSPEC burst, and time-tagged event (TTE) data (Meegan et al. 2009; Kaneko et al. 2010). The TTE data consist of time-tagged photon events for an accumulation time of $\sim$330 s, starting $\sim$30 s before the trigger time, with a superior temporal resolution of 2 μs and a fine spectral resolution of 128 energy channels.

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, R.A., decl. (J2000) = 70.0, +55.6 ($4^{\mathrm{h}}40^{\mathrm{m}}$, $+55^\circ35'$) and 60.5, +55.4 ($4^{\mathrm{h}}02^{\mathrm{m}}$, $+55^\circ22'$), are shown in Figure 1 (top panels). 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 2008 August (shown in the Figure 1 top panels). 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 are also displayed. Subsequent ground analysis of the BAT data revealed a weak source at R.A., decl. (J2000) = 64.606, +57.489 ($4^{\mathrm{h}}18^{\mathrm{m}}25^{\mathrm{s}}$, $+57^\circ29'16''$) with an uncertainty of $4'$, which is consistent with the GBM localizations for both events (right upper panel of Figure 1). The annuli clearly exclude the position of SGR J0501+4516; the distance between the two sources is $\sim$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).

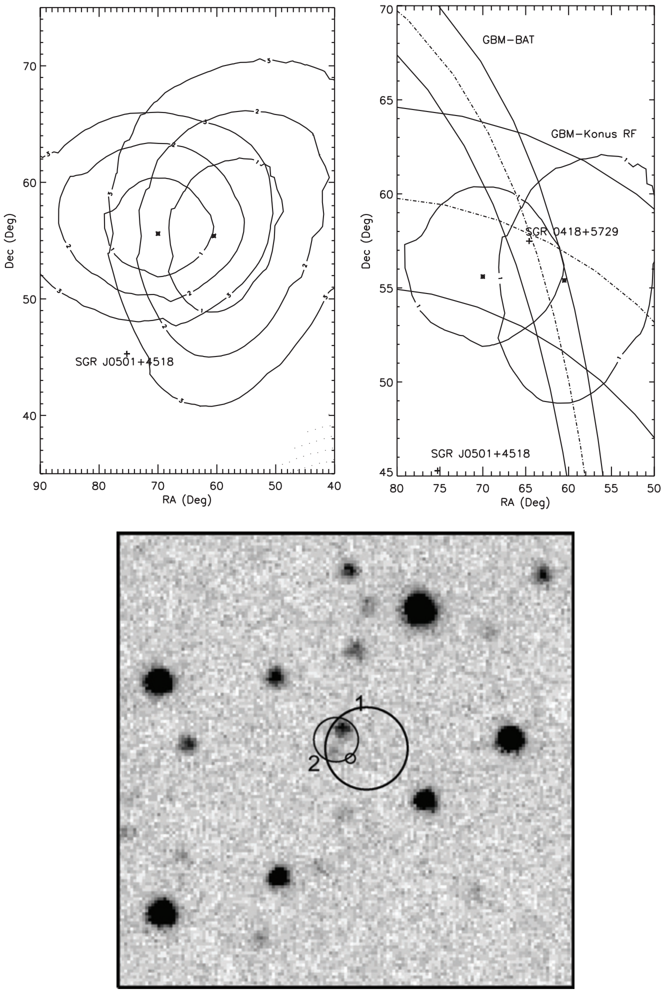

Figure 1. Top left: GBM localizations (asterisks) for the two SGR J0418+5729 triggers on 2009 June 5. The contours indicate 1, 2, and 3σ statistical uncertainties. The position of the known SGR J0501+4516 is also shown. It is marginally consistent with the GBM events if one takes into account an additional 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 the 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_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.

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

The *Swift*/X-Ray Telescope (XRT) observed SGR J0418+5729 starting 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 R.A. = $04^{\mathrm{h}}18^{\mathrm{m}}33^{\mathrm{s}}.70$, decl. = $+57^\circ32'23''.7$ (J 2000) with an error circle radius of $3''.6$. The XRT location is shown in Figure 1 (bottom panel) and is $\sim 3'.3$ 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. We constructed a binned (by a factor of 2)

Table 1
Chandra/HRC Coordinates of SGR J0418+5729 and the Two X-ray Sources with IR Counterparts

Source	R.A.	Decl.
SGR J0418+5729	$04^{h}18^{m}33^{s}.867$	$+57°32'22''.91$ (J2000)
CXOU J041819.0+573341	$04^{h}18^{m}19^{s}.097$	$+57°33'41''.75$ (J2000)
CXOU J041812.5+573154	$04^{h}18^{m}12^{s}.578$	$+57°31'54''.99$ (J2000)

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 uncataloged 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 (bottom 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 5 m Palomar Hale telescope on 2009 August 2 (Wachter et al. 2009). WIRC has a field of view of $8'.7 \times 8'.7$ and a pixel scale of $0''.2487$ pixel^{-1}. We obtained 26 K_s band images using two 13 position dither scripts (the second script spatially offset from the first)—each position was a co-added exposure of 12 five-second images. Atmospheric conditions were very good with seeing $<1''$ and clear skies during observations.

The individual frames were reduced using a suite of IRAF[20] scripts and FORTRAN programs. These scripts first linearize and dark-subtract the images. A sky frame and a 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 Two Micron All Sky Survey (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 mosaiced together and the mosaic was photometrically calibrated using 2MASS stars. Vega magnitudes were computed using the IRAF phot routine with the zero points as found using the 2MASS stars. The final image (see the bottom panel of Figure 1) has a 5σ K_s detection limit of 19.6 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 right ascension (R.A.) based on those two sources and no systematic difference in declination (decl.). The X-ray positions in Table 1 have been corrected for this shift and are thus registered to the 2MASS astrometric reference frame.

Our K_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 (labeled 1 and 2 in the Figure 1 bottom panel) with $K_s = 17.66 \pm 0.04$ and $K_s = 18.8 \pm 0.1$, respectively, 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 $K_s = 21.6 \pm 1.3$ 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 GBM continuous data files for untriggered bursts from SGR J0418+5729 using the algorithm described by Kaneko et al. (2010) starting 2 days before the two triggered events and ending 6 days after. 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 minutes 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.

Additionally, a search through $\gtrsim$4000 IPN events with fluences $\gtrsim 7 \times 10^{-6}$ 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 Letter.

We have performed detailed temporal and spectral analysis on the two triggered events using the TTE data type. The third (untriggered) event was only detected above background as one 256 ms bin in the continuous CTIME data. Since the CTIME data spectral resolution is relatively coarse (only eight 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.[21] We generated detector response matrices using *GBMRSP v1.81*. For both events, we used in our analysis the three NaI detectors with the smallest zenith angles (ranging from 26° to 44°) to the source, i.e., NaI's 3, 4, and 5. 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

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[20] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[21] 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.

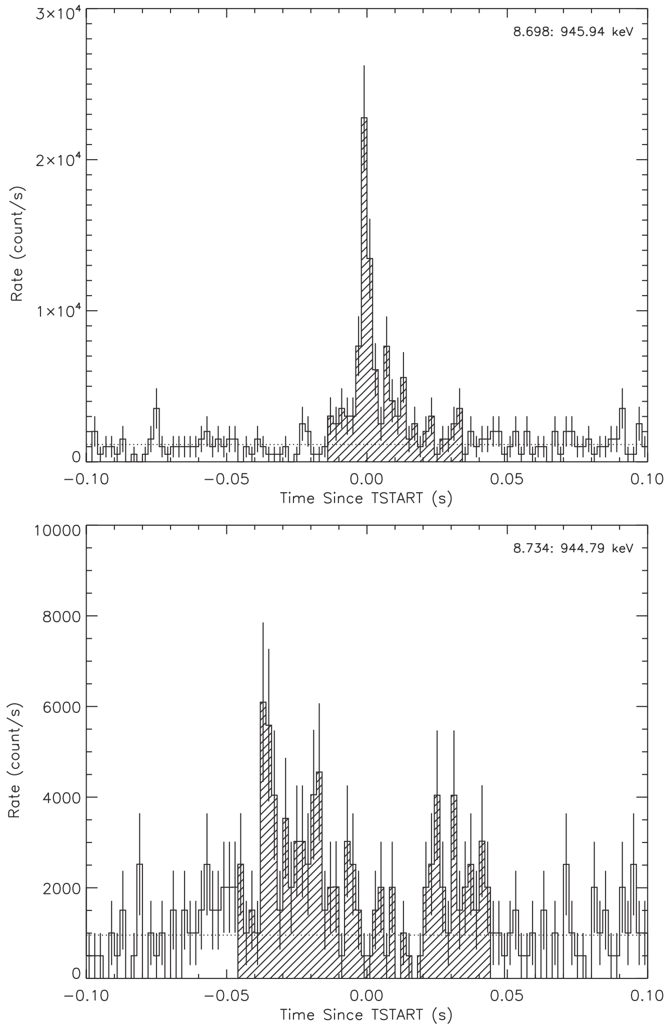

Figure 2. TTE light curves of the two SGR J0418+5729 triggered events. The hatched areas indicate the time intervals used for spectral analysis.

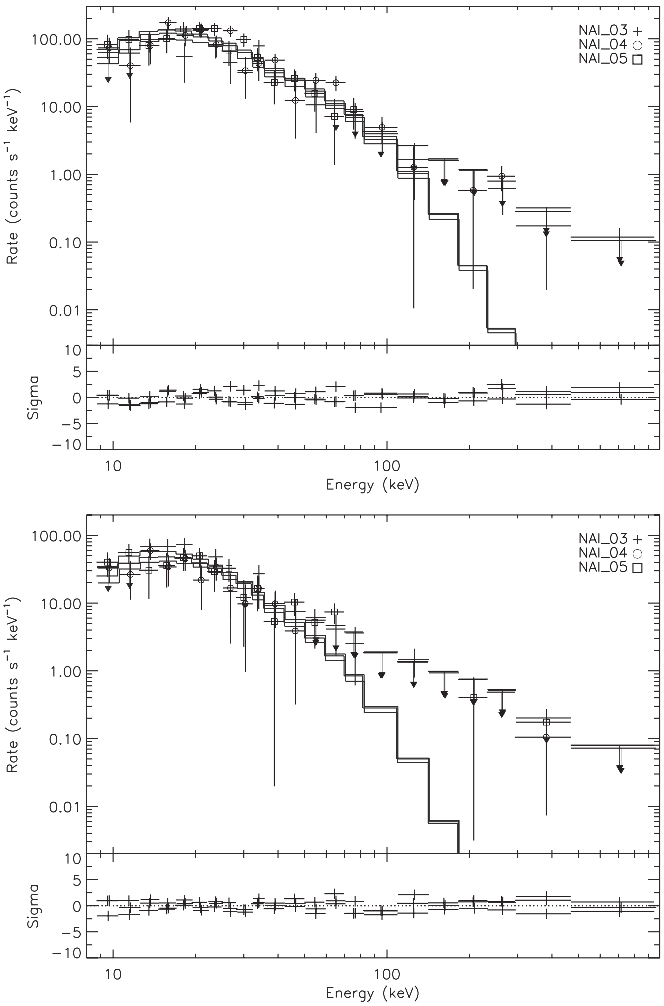

Figure 3. Best-fit OTTB count spectra of the two SGR J0418+5729 triggered events.

trigger we find $T_{90}(T_{50}) = 40 \pm 7$ ms (10 ± 4 ms), 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. 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 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 cutoff power law gives a better statistics value (Table 2), which is not statistically significant given that this model has one 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 (8–200 keV) 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) but at the high end for AXP ones (Gavriil et al. 2004). We note that an OTTB fit to the CTIME continuous data of the third (untriggered) event implies an energy (8–200 keV) 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		Cutoff Power Law			Energy Flux
(UT)	kT (keV)	cstat/dof	Index	$E_{\rm peak}$ (keV)	cstat/dof	(8–200 keV) (10^{-6} erg cm^{-2} s^{-1})
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

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 s 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; Mignani et al. 2009; Ratti et al. 2009; Lorrimer et al. 2009). 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 (P. M. Woods et al. 2010, 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 ~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, we would not have detected them. This raises the question: what is the population of such "dim" SGRs? A very rough estimate comparing two SGRs at ~2 kpc versus four at ~10 kpc, and assuming a uniform distribution within the Galactic plane, gives ~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 (1) fixed membership, and (2) 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 toward 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 (five) found by all instruments in the 30 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 four SGRs, two old and two 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 & Heyl 2007; Leahy & Ouyed 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 J0418+5729 indicates, it might significantly contribute to and increase the magnetar birth rate.

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