Searches for gamma-ray emission from magnetar candidates SGR 0501+4516 and 1E 1547.0-5408 with the $Fermi$ LAT

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***Abstract*. Soft Gamma-ray Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs) are believed to be strongly magnetized isolated neutron stars powered by the decay of their magnetic field, labeled for this reason as "magnetars". They exhibit episodes of bursting and flaring activity mostly in the soft and hard X-ray range. Since August 2008, the Large Area Telescope on the $Fermi$ Gamma-ray Space Telescope ($Fermi$ LAT) has been surveying the entire sky in gamma rays of energies ranging from 20 MeV to $>$300 GeV. During that time, the magnetar candidates SGR 0501+4516 and 1E 1547.0-5408 entered an active burst phase, which was continuously monitored by the $Fermi$ LAT thanks to its large field of view. We present here the results of a search for gamma-ray emission from these two magnetar candidates.**

***Keywords*: gamma rays, magnetars, neutron stars**

I. INTRODUCTION

Highly magnetized neutron stars (aka "magnetars") recently underwent a phase of renewed interest in high-energy astrophysics. These extreme objects comprise the Anomalous X–ray Pulsars (AXPs) and Soft Gamma–ray Repeaters (SGRs), two classes of sources observationally very similar in many respects (see [1] for a recent review). They are all slow X–ray pulsars with spin periods clustered in a narrow range ($P \sim$ 2–12 s), relatively large period derivatives ($\dot{P} \sim 10^{-13}$–10^{-10}s s^{-1}), spin-down ages of $10^3 - 10^4$ yr, and magnetic fields of $10^{14} - 10^{15}$ G inferred from the classical magnetic dipole spin-down formula and larger than the electron quantum critical field ($B_{cr} \simeq 4.4 \times 10^{13}$ G). AXPs and SGRs are usually strong persistent X-ray emitters, with X-ray luminosities of about $10^{34} - 10^{36}$ erg s^{-1}, and, although other models are not completely ruled out, within the "magnetar model" their powering mechanism is related to the ultra-strong magnetic field of the neutron star [2][3].

In the 0.1–10 keV energy band, magnetar persistent spectra are relatively soft and usually modeled by an absorbed blackbody (kT$\sim$0.2–0.6 keV) plus a power-law ($\Gamma \sim$2–4) or a resonant cyclotron scattering model [4]. Thanks to *INTEGRAL*–ISGRI and *R*XTE–HEXTE, hard X–ray emission up to $\sim$200 keV has been recently detected for some sources [5][6].

At variance with other isolated neutron stars, magnetar candidates exhibit spectacular episodes of bursting and flaring activity, during which their luminosity may change up to 10 orders of magnitude on sub-second timescales. In particular, they are characterized by periods of activity during which they emit numerous short bursts in the hard X-ray/soft gamma-ray energy range ($t \sim 0.1 - 0.2$ s; $L \sim 10^{38} - 10^{41}$ erg s^{-1}). This is indeed the defining property of this class of sources. In addition, they have been observed to emit *intermediate flares*, with typical duration of $t \sim 1 - 60$ s and luminosity of $L \sim 10^{41} - 10^{43}$ erg s^{-1}, and spectacular *Giant Flares*. The latter are rare and unique events in the X-ray sky, by far the most energetic Galactic events currently known ($\sim 10^{44} - 10^{47}$ erg s^{-1}), second only to Supernova explosions. However, these different types of bursts/flares do not seem to repeat in a regular, predictable way.

The magnetar idea was originally proposed to explain the very extreme properties of their bursts and flares: the frequent short bursts would then be associated with small cracks in the neutron-star crust, driven by magnetic diffusion, or, alternatively, with the sudden loss of magnetic equilibrium through the development of a tearing instability, while the giant flares would be linked to global rearrangements of the magnetic field in the star magnetosphere and/or interior. Giant flares have been so far observed only three times from the whole sample of SGRs, and never twice from the same source. As far as short bursts and intermediate flares are concerned, while some SGRs (as SGR 1806-20) are extremely active sources, in other cases no bursts have been detected for many years (as in the case of SGR 1627-41, that re-activated last May after a 10-yr long stretch of quiescence; [7][8]). This suggests that a relatively large number of members of this class has not been discovered yet. Such objects may manifest themselves in the future through a phenomenology (bursts) similar to that displayed by most of the currently known member of this class.

The $Fermi$ Gamma-ray Space Telescope, launched on the 11th of June 2008, carries two instruments on board: the Large Area Telescope (LAT)[9] and the

Gamma-ray Burst Monitor (GBM). The LAT is a pair-conversion gamma-ray detector sensitive to the 20MeV–300GeV energy range. After an initial activation and on-orbit calibration, the LAT commenced normal science operations on the 4th of August 2008. Thanks to its wide field of view (∼2.4 sr at 1 GeV), it observes the entire sky every ∼3 h (∼2 orbits). The LAT has a large effective area (∼8000 cm^2 for $E > 1$ GeV on axis), and a good (for a gamma-ray detector) angular resolution (68% of the point spread function is contained in $\sim 0.8^o$ at 1 GeV). The GBM is dedicated to the search of gamma-ray bursts, and because of this it is sensitive to any kind of transient emissions (such as from magnetars). It consists of 12 sodium iodide (NaI) and two bismuth germanate (BGO) detectors, it is sensitive in the 8 keV–40 MeV energy range, and it has a wide field of view (∼8 sr).

During the life of the $Fermi$ mission, three powerful outbursts (periods of intense bursting activity) have been observed from magnetars: one in August 2008 leading to the discovery of a new member of the magnetar class, SGR 0501+4516 [10], and two in October 2008 and January 2009 from the well known magnetar candidate 1E 1547.0-5408 [11]. The detected emissions extended in some cases up to ∼400 keV [12][13]. An extrapolation of their spectra to the LAT energy range (E>20 MeV) shows that they would likely be too weak to be detected by the LAT. However, it would still be interesting to examine the LAT data during these bursts, in case a separate high energy component – never before detected – is also present. For this reason, the LAT data were searched for transient emissions in coincidence with magnetar bursts detected by other instruments (sectio II). In the case of 1E 1547.0-5408, given its hard X-ray persistent spectrum, we also searched for emission integrating during the whole outburst (and not only in coincidence with the individual bursts), as well as using all the $Fermi$ LAT data available until mid-April 2009 (section III).

II. Triggered Searches for Transient Emissions

The LAT data were searched for transient emissions from SGR 0501+4516 and 1E 1547-5408. The analysis described in this section is for a "triggered" search, in the sense that the LAT data were searched *only* during magnetar-related activity detected by other instruments. Searches for transient emissions on many time scales and independently on the times of any detected bursts ("blind searches") are also underway and will be presented in a future paper. Based on the data availability and the matching fields of view between the LAT and the GBM, the LAT data were searched in coincidence with the GBM-detected magnetar bursts. Up to April 17th 2009, the GBM has triggered 131 times from 1E 1547-5408, and 26 times from SGR 0501+4516. The GBM data produced after each of these triggers contained one or more narrow (tens to hundreds of ms duration) spikes of emission. The first step of this analysis was to analyze the GBM data to extract the times of these spikes.

One of the GBM data products is the "continuous time" (CTIME) data, consisting of the event rate in each of its 12 NaI and 2 BGO detectors at 8 energy channels. The CTIME data are saved with a time resolution of 64 ms for 600 s after each trigger, and with a lower resolution at other times. This analysis used the increased time-resolution (64 ms) CTIME data. The list of the GBM magnetar-related triggers was obtained from the GBM Magnetar Project page[1], and the GBM data were obtained from the HEASARC database[2].

For each GBM trigger, the CTIME data of the NaI detectors showing evidence of a signal were combined to a single light curve. This light curve consisted of a smoothly varying background with narrow and intense signal-spikes superimposed on it (fig. 1). To be able to detect these spikes and estimate their statistical significance correctly, the value of the background at each of the 64 ms time bins had to be estimated first. The background estimate at some time t_1 was produced by averaging the event rates in an extended time interval of duration 200 ms around t_1. This duration was long enough to have good statistics for the background estimation, and short enough to be able to follow short-time-scale changes of the background. To minimize the contribution from magnetar emissions in the background estimates, any data points that were noticeably distant (roughly $\sim 3\sigma$) from the main distribution were not included in the averages.

The next step was to detect the narrow emission spikes over the now-known smoothly varying background. A simple algorithm was used to detect the spikes. Initially, the light curves were scanned for blocks of adjacent data points, in which the 64 ms event rate was always higher than the expected background by at least 1.5σ. This statistical significance was simply the difference between the measured and estimated-background rates divided by the square root of the estimated background rate. Then, for each of the detected blocks, the event rates and the expected backgrounds of each of their constituting 64 ms data points were added, and an aggregate "block significance" was calculated. If the aggregate significance of a block was over 7.5σ, then the information of that block was added to a list for further analysis. The significance limit (7.5σ) was chosen by considering the amount of trials involved in this search. For example, for 1E 1547-5408, taking account the number of analyzed triggers (138), the amount of data points per trigger (equal to 600/0.064), the effective number of ways these data points can combine to generate significant blocks of larger durations (~ 5) yields an effective number of trials equal to about 7×10^6. Therefore, to select the undoubtedly significant blocks (say with a post-trials probability $\lesssim 3\times10^{-7}$ or $\gtrsim 5\sigma$) we would need to apply

[1]http://gammaray.nsstc.nasa.gov/gbm/science/magnetars/
[2]http://heasarc.gsfc.nasa.gov/

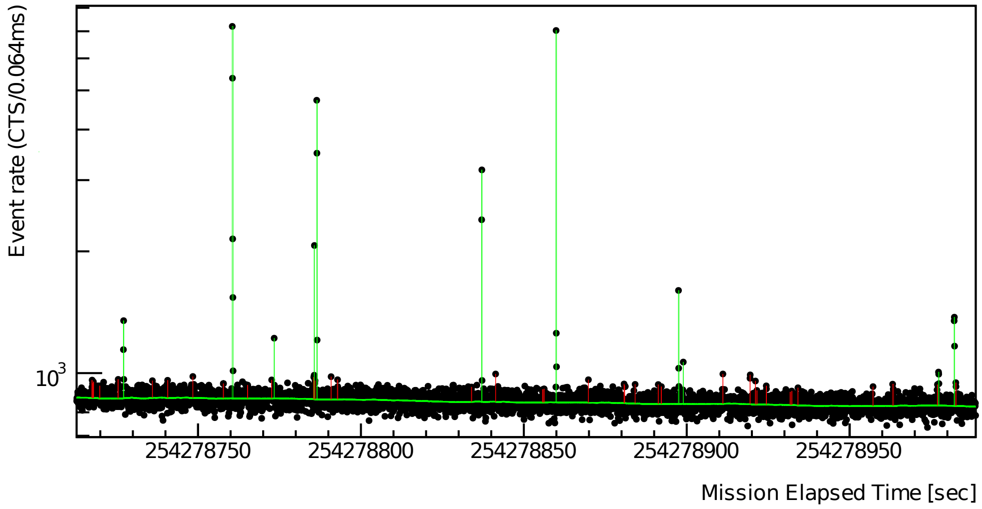

Fig. 1. A light curve generated by GBM data produced after a trigger from 1E 1547-5408. The black dots show the event rates in 64 ms intervals, the horizontal green line is the estimated background, and the vertical bars show the detected spikes. The short red vertical bars show the spikes with a pre-trials significance between 2.5 and 7.5σ, and the long green vertical bars show the spikes selected for further LAT analysis (significance $> 7.5\sigma$).

Source	***UL on the flux of individual spikes*** $[erg/(cm^2\,s)]$		***UL on the average flux*** $[erg/(cm^2\,s)]$	
	a=-2	***a=-3***	***a=-2***	***a=-3***
SGR 0501+4516	3×10^{-3}–3×10^{-2}	8×10^{-3}–8×10^{-2}	6×10^{-4}	2×10^{-3}
1E 1547-5408	5×10^{-4}–5×10^{-2}	1×10^{-3}–2×10^{-1}	4×10^{-5}	9×10^{-5}

TABLE I

PRELIMINARY 90% CONFIDENCE LEVEL UPPER LIMITS (UL) ON THE FLUX OF SELECTED MAGNETAR BURSTS IN THE 20 $MeV - 300\,GeV$ ENERGY RANGE. COLUMNS TWO AND THREE SHOW THE UPPER LIMITS FOR INDIVIDUAL SPIKES, AND THE RIGHT TWO COLUMNS SHOW THE UPPER LIMITS ON THE AVERAGE FLUX PER SPIKE (OBTAINED BY STACKING THE RESULTS FROM ALL INDIVIDUAL SPIKES).

Time-Period	Test Statistic	Power-Law index	Integral Flux ($ph\cdot cm^{-2}\cdot s^{-1}$)
Outburst Period	12	-2.00 ± 0.24	$0.49\pm0.29\times10^{-9}$
8 months of LAT Data	17	-2.04 ± 1.42	$0.14\pm0.62\times10^{-9}$

TABLE II

PRELIMINARY RESULTS OF A MAXIMUM-LIKELIHOOD TEST FOR PERSISTENT EMISSION FROM MAGNETAR CANDIDATE 1E 1547-5408 FOR TWO DIFFERENT TIME PERIODS. THE TEST STATISTICS (TS) OF BOTH TESTS ARE NOT SIGNIFICANT ENOUGH TO CLAIM A DETECTION. FOR MORE INFORMATION ON THE TS SEE [16]. FOR REFERENCE, A TS=25 CORRESPONDS TO A STATISTICAL SIGNIFICANCE OF 4.6σ. THE RESULTS CORRESPOND TO THE 200 MEV-200 GEV ENERGY RANGE.

a significance cut of at least $(3\times10^{-7})/(7\times10^{6}) \simeq 4\times10^{-14}$ or $\sim7.5\sigma$. Figure 1 shows the results of the search for one of the triggers from 1E 1547-5408.

After all the data had been analyzed, any spikes occurring when the source was not in the LAT's field of view or near the Earth's limb were removed from the list of significantly ($> 7.5\sigma$) detected GBM spikes. The remaining list contained 250 spikes from 1E 1547-5408 (68 s total duration), and 11 spikes from SGR 0501+4516 (3.6 s total duration). The durations of individual spikes ranged from 64 ms (1 time bin) to 1.2 sec (20 time bins). The typical (median) duration of a spike was about 180 ms.

Next, the "transient-class" LAT data produced exactly during the remaining spikes were searched for transient emissions. The "transient-class" LAT data are produced using a set of cuts that corresponds to an increased effective area at the expense of a somewhat increased background contamination [9], appropriate for signal-limited searches of short transient signals. The energy range of the examined LAT data was 20 MeV–300 GeV. The radius of the region of interest (ROI) was equal to the radius that encloses 95% of the point spread function. For each spike, the expected number of LAT background events ($< N_{exp} >$) was estimated, the detected events ($< N_{det} >$) were counted, and the Poisson probability of detecting at least $< N_{det} >$ events while expecting $< N_{exp} >$ was calculated. The background estimate ($< N_{exp} >$) included both components of the LAT background: cosmic rays and gamma rays. The cosmic-ray component of the background was calculated based on its dependence on the geomagnetic coordinates at the location of the spacecraft and the dependence of the LAT's acceptance on the off-axis and azimuthal angle of an event. The gamma-ray component of the background estimate was equal to the amount of gamma rays actually detected from the direction of the source during the first 8 months of the LAT mission multiplied by the ratio of the exposure of the observation under consideration (the magnetar spike) over the exposure of the 8-months dataset. The background estimate produced using this method was tested with real data and was found to be accurate to within 10-15%. For more information on the background estimation procedure see [14]. Taking into account the number of trials (equal to the number of examined spikes), the numbers of events detected by the LAT during each of these spikes were consistent with being mere fluctuations of the background. The data of the individual spikes were also stacked, and an aggregate probability was calculated using the sum of the expected and detected numbers of events, yielding the same null result.

Since there were no detections, an upper limit on the 20 MeV–300 GeV magnetar bursting emission was placed. Using $< N_{exp} >$ and $< N_{det} >$ for each burst, and following the Feldman-Cousins confidence-intervals construction [15], upper limits on the number of detected by the LAT events were calculated. Then, using the response of the LAT for each individual observation, and assuming a spectral index for the emission in the LAT energy range, upper limits were placed on the flux of each burst. The 90% confidence level upper limits on the flux for two spectral indices ($a = -2$ and $a = -3$ with $dN/dE \propto E^a$) are shown in Table I. The upper limits for individual spikes varied from burst to burst because, among others, each burst was observed under a different off-axis angle (hence with a different LAT sensitivity).

III. SEARCH FOR PERSISTENT EMISSION FROM 1E 1547-5408

The magnetar candidate 1E 1547-5408 was also analyzed integrating over two different continuous periods, in search for a persistent high-energy emission rather than only from the single bursts. We searched in all the available LAT data (Aug. 4th 2008 – April 2nd 2009, ~8 months), and also in the outburst period (Jan. 17th to 31st 2009). We used the maximum-likelihood spectral estimator *gtlike*, a tool that is part of the standard analysis software of the $Fermi$ LAT collaboration. This tool essentially fits a source model to the data. The galactic and extragalactic diffuse emissions, and nearby point sources (found in the $Fermi$ LAT's bright gamma-ray source list [16]) were included in the model. The galactic diffuse emission was modeled using GALPROP [17][18], a code that uses a realistic representation of cosmic-ray propagation in the Galaxy to calculate the resulting gamma-ray galactic diffuse emissions. The extra-galactic component, the magnetar source, and all the other sources in the region of interest were modeled with a simple power-law spectrum. For more information on the likelihood test and how to interpret its resulting Test Statistic see [16]. The analyzed data set was produced using the "diffuse-class" cuts, a set of cuts that corresponds to a somewhat decreased effective area at lower energies with the benefit of a significantly reduced background contamination, appropriate for background-limited searches for long persistent emissions.

The results of the likelihood fits are shown in Table II. The statistical significance of the results for both tested time periods is not high enough to claim a detection.

IV. CONCLUSION

A search in the LAT data did not find any counterpart to the single bursts from SGR 0501+4516 and 1E 1547-5408, hence we put some preliminary upper limits on the spectrum of such bursts at the 20 MeV–300 GeV energy range. A search for persistent emission from 1E 1547-5408 also failed to reach a detection. However, the somewhat elevated statistical significance of the persisent-emission result hints that a significant detection might be reached after more data have been accumulated. The analyses and results in this proceeding are preliminary. The final results will be presented in a dedicated paper on magnetar observations with the LAT, currently in preparation.

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