GAMMA-RAY UPPER LIMITS ON MAGNETARS WITH SIX YEARS OF FERMI-LAT OBSERVATIONS

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ABSTRACT

We report on the search for gamma-ray emission from 20 magnetars using six years of Fermi Large Area Telescope observations. No significant evidence for gamma-ray emission from any of the currently known magnetars is found. We derived the most stringent upper limits to date on the 0.1–10 GeV emission of Galactic magnetars, which are estimated between $10^{-12}$ and $10^{-11}$ erg s$^{-1}$ cm$^{-2}$. We searched gamma-ray pulsations for the four magnetars having reliable ephemerides over the observing period, but detected none. We also report updated morphologies and spectral properties of seven spatially extended gamma-ray sources, which are most likely attributed to supernova remnants associated with or adjacent to the magnetars.

Key words: gamma-rays: stars – stars: magnetars – X-rays: stars

1. INTRODUCTION

Magnetars (comprising anomalous X-ray pulsars and soft gamma repeaters; AXPs and SGRs) are a small group of X-ray pulsars (about 20 objects), with spin periods between 0.3 and 12 s. Their inferred magnetic fields, assuming the spin-down dipolar loss formula ($B = 3.2 \times 10^{19} \sqrt{P} P$ G, $P$ is the spin period and $P$ is its first derivative), appear to be in general as high as $B \sim 10^{14} - 10^{15}$ G. Due to these high magnetic fields, the emission of magnetars is thought to be powered by the decay and instability of their strong fields (Duncan & Thompson 1992; Thompson & Duncan 1993; Thompson et al. 2002). The powerful X-ray output is usually well modeled by thermal emission from the neutron star hot surface (about 0.2–0.6 keV), reprocessed in a twisted magnetosphere through resonant cyclotron scattering, a process favored only under these extreme magnetic conditions. On top of their persistent X-ray emission, magnetars emit very peculiar flares and outbursts on several timescales (from fractions of seconds to years) releasing a large amount of energy ($10^{46} - 10^{48}$ erg). These flares are probably caused by large-scale rearrangements of the surface/magnetospheric field, either accompanied or triggered by displacements of the neutron-star crust. See Mereghetti (2008), Rea & Esposito (2011), and Olausen & Kaspi (2014) for recent reviews. Thanks to INTEGRAL, Suzaku, and NuSTAR we now have good spectra for magnetars in the hard X-ray energy range (Kuiper et al. 2004; Enoto et al. 2010; An et al. 2015).

The gamma-ray emission (0.1–300 GeV band) from 13 magnetars has been searched using the first 17 months of Fermi-LAT data (Abdo et al. 2010a). This search resulted in upper limits and no pulsations were found. Taking advantage of about five more years of data, in this paper we re-analyze the Fermi-LAT observations for the previous objects, as well as for seven magnetars that were discovered in the meantime. Furthermore, the better response of the instrument at lower energies brought about by Pass 8 (Atwood et al. 2013) allows us to undertake a more stringent search.

In Section 2 we report on the Fermi-LAT analysis procedure; we summarize our results in Sections 3 and 4, and provide a discussion of our findings in Section 5.

2. OBSERVATIONS AND DATA ANALYSIS

The Fermi-LAT data included in this paper covered 74 months from 2008 August 4 to 2014 October 1, which greatly extended the 17 month data coverage of Abdo et al. (2010a). The analysis of the Fermi-LAT data was performed using the Fermi Science Tools (FST) 4.0.34.01 release. Events from the Pass 8 source class were selected. The P8 SOURCE V5 instrument response functions (IRFs) were used for the analysis. All gamma-ray photons within an energy range of 0.1–300 GeV and within a circular region of interest of 10$^5$ radius centered on each source analyzed were used for the analysis. To reject contaminating gamma-rays from the Earth’s limb, we selected events with zenith angle <100$^\circ$, or <90$^\circ$ for sources with high possibility of contamination (high-latitude sources with decl. >45$^\circ$, underlined in Table 1). The gamma-ray flux and spectral results presented in this work were calculated by performing a binned maximum likelihood fit using the Science Tool gtlike. The binned maximum likelihood analysis was carried out on a 14$^2$1 x 14$^2$1 square region with a pixel size of 0.1 centered on each magnetar. A total of 30 bins in the 100 MeV–300 GeV range were used in the analysis. The spectral/spatial model constructed to perform the likelihood analysis includes Galactic and isotropic diffuse emission components (“gll_iem_v06.fits,” Acero et al. 2016b, and “iso_P8R2_SOURCE_V6_v06.txt,” respectively) as well as known gamma-ray sources within 15$^\circ$ from the magnetars, following the internal six year source list which was based on “Pass 8” Fermi-LAT data covering 2008 August 4 to 2014 August 4. The spectral parameters were fixed to the catalog values, except for the sources within 3$^\circ$ from the magnetars. For these latter sources, all the spectral parameters were left free.

The magnetars in Table 1 were modeled with a simple power law with all spectral parameters allowed to vary. The maximum likelihood test statistic (TS) was employed to evaluate the

http://fermi.gsfc.nasa.gov/ssc/

The Science Tools and IRFs used here are internal pre-release versions of the Pass 8 data analysis. Our results did not change substantially with the final release versions.

http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html
The significance of the gamma-ray fluxes coming from the magnetars. The test statistic is defined as $TS = -2 \ln (L_{max,0}/L_{max,1})$, where $L_{max,0}$ is the maximum likelihood value for a model without an additional source (the “null hypothesis”) and $L_{max,1}$ is the maximum likelihood value for a model with an additional source at a specified location. A larger TS indicates that the null hypothesis is incorrect (i.e., a source is detected). The square root of the TS is approximately equal to the detection significance of a given source. We set the detection threshold to be $TS > 25$. The 95% flux upper limits for magnetars are calculated following Helene’s method (Helene 1983) assuming a power-law spectral shape. In the 0.1–10 GeV energy range, we fixed the photon index at 2.5, as in Abdo et al. (2010a). In the 0.1–1 GeV and 1–10 GeV ranges, the upper limits are evaluated using a photon index fixed at 1.5 and 3.5 respectively, mimicking a spectral cutoff at $\sim$1 GeV, as is common in pulsar spectra. Apart from the photon index, other spectral parameters in the upper limit calculation are the same as in the $glike$ analysis. For the extended source analysis, we followed the method as described in Lande et al. (2012). We assumed the source to be spatially extended with a symmetric disk model and fitted its position and extension with the $pointlike$ analysis package (Kerr 2011) between 0.1 and 300 GeV. Following the method in Lande et al. (2012), the TS value of the putative extension is defined as $TS_{ext} = 2(\ln L_{disk} - \ln L_{point})$, in which $L_{disk}$ and $L_{point}$ are the $glike$ global log likelihood of the extended source and point source hypothesis, respectively. We set the threshold for claiming the source to be spatially extended as $TS_{ext} > 16$ corresponding to a significance of $\sim 4\sigma$. TS maps shown in this paper are produced with the $pointlike$ analysis tool. In most cases, the Fermi-LAT data could be well modeled by the sources from the internal six year source list. In the case of excesses in the residual TS map, extra point sources were added following a similar method to that described in Caliandro et al. (2013), Section 3.3.3.

3. RESULTS

We studied the Fermi-LAT observations of all confirmed magnetars from the McGill Online Magnetar Catalog (Olausen & Kaspi 2014), except for the extragalactic ones and the Galactic center magnetars due to the difficulty of resolving them from their respective environments (see Abdo et al. 2010b, 2010c). Those are: SGR 0526–66 in the Large Magellanic Cloud, CXOU J010043.1–721134 in the Small Magellanic Cloud, and SGR 1745–2900 at the Galactic center. We list in Table 1 the results for the 20 selected magnetars.

Most of the magnetars are clearly undetected, having TS values <25 in the $glike$ analysis. This is the case for SGR 0418+5729, 4U 0142+614, Swift J1823.3–1606, SGR 1900+1402, 1E 1048.1–5937, and SGR 1818–0532. No gamma-ray source is associated with these 10 magnetars.

Table 1: Fermi-LAT Upper Limits on Magnetars as Obtained from the Likelihood Analysis

| Source                  | TS   | TS         | 0.1–1 GeV | 1–10 GeV | 0.1–10 GeV |
|-------------------------|------|------------|-----------|----------|-----------|
|                         |      | (Abdo et al. 2010a) |           |          |           |
| SGR 0418+5729           | 0.0  | 2.3        | <0.18     | <0.05    | <0.15     | 3         |
| 4U 0142+614             | 0.0  | 3.6        | <0.43     | <0.07    | <0.29     | 3         |
| Swift J1823.3–1606      | 0.0  |            | <0.88     | <0.13    | <0.43     | 19        |
| Swift J1834.9–0846      | 0.0  |            | <0.85     | <0.52    | <0.55     | 19        |
| 1E 1048.1–5937          | 0.0  | 0.0        | <0.51     | <0.53    | <1.10     | 35        |
| XTE J1810–197           | 0.0  | 13.1       | <1.00     | <0.89    | <3.65     | 17        |
| SGR 0501+4516           | 0.0  | 16.3       | <0.53     | <0.08    | <0.38     | 4         |
| PSR J1622–4950          | 0.8  |            | <1.98     | <0.63    | <1.00     | 26        |
| 1E 1841–04b             | 1.0  | 7.5        | <1.13     | <0.94    | <2.05     | 23        |
| 3XMM J18524.6+003317b   | 2.5  |            | <1.33     | <0.48    | <2.03     | 23        |
| 1E 2259–386 b           | 2.8  | 15.6       | <0.21     | <0.13    | <0.13     | 13        |
| SGR 1806–20             | 2.9  | 2.8        | <2.38     | <0.50    | <0.67     | 15        |
| SGR 1935+2154           | 3.5  |            | <0.11     | <0.22    | <0.17     | 6         |
| 1E 1547.0–5408          | 4.2  | 36.2       | <1.40     | <0.90    | <2.84     | 14        |
| SGR 1990+14             | 4.5  |            | <0.68     | <0.49    | <1.52     | 13        |
| CXOU J164710.2–455216   | 6.0  |            | <0.96     | <0.45    | <0.89     | 27        |
| 1RXS J170849.0–400910   | 6.6  | 32.1       | <2.14     | <0.96    | <2.51     | 15        |
| SGR 1627–41b            | 15.9 | 36.0       | <3.39     | <1.78    | <2.06     | 29        |
| SGR 1833–0832b          | 21.1 |            | <2.92     | <0.97    | <0.86     | 19        |
| CXOU J171405.7–381031c  | 50.9 |            | <0.24     | <0.46    | <0.70     | 11        |

Notes. Fluxes in the different energy ranges are in units of $10^{-11}$ erg cm$^{-2}$ s$^{-1}$. Properties of the magnetars studied in this work, ordered by the measured TS values derived from the binned analysis. The magnetars underlined have zenith angle cut at 90° (see Section 2 for details). The GeV upper limits are reported at the 95% confidence level (see Section 2 for details).

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4. RESULTS

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Most of the magnetars are clearly undetected, having TS values <25 in the $glike$ analysis. This is the case for SGR 0418+5729, 4U 0142+614, Swift J1823.3–1606, SGR J1622–4950, 1E 1048.1–5937, XTE J1810–197, SGR 1806–20, SGR 1935+2154, CXOU J164710.2–455216, and 1E 1547.0–5408. No gamma-ray source is associated with these 10 magnetars in the TS maps. Upper limits are evaluated for these magnetars.

The uncertainties of the Fermi-LAT effective area and of the Galactic diffuse emission are the two main sources of systematics that can affect the evaluation of the upper limits to a different extent on individual sources. These systematic effects are estimated by repeating the upper limit analysis using

http://www.physics.mcgill.ca/~pulsar/magnetar/main.html

A study of this region was reported by Yeung et al. (2016).
modified IRFs that bracket the effective areas and changing the normalization of the Galactic diffuse model artificially by ±6%, similar to Abdo et al. (2010a), for all magnetars considered in this paper.9 Energy dispersion is not considered in the data analysis, which may be important below 100 MeV, but is not expected to produce significant changes in the 100 MeV–300 GeV energy range considered in this work. The results of this analysis are reported in Table 1.

Below we comment on a case-by-case basis on all magnetar locations that resulted in a high TS value since they are either associated with or adjacent to a Fermi-LAT detected supernova remnant (SNR), or located in a crowded region.

3.1. Magnetsars with Associated SNRs

3.1.1. 1E 1841−045

SNR Kes 73 is associated with 1E 1841−045. This SNR was listed as "Other Detected Candidate Source" in the first Fermi-LAT SNR Catalog (Acero et al. 2016a). Its gamma-ray association was not confirmed by the spatial coincidence analysis in Acero et al. (2016a). A gamma-ray point source from the internal six year source list is located only 0°.16 away from 1E 1841−045 (Figure 1), which was excluded from the spatial model. The pointlike TS map of 1E 1841−045 showed an extended source peak at the magnetar (Figure 1, top left panel). The source is not present in the third Fermi Source Catalog (Acero et al. 2015, 3FGL hereafter) but it is spatially coincident with the source from the internal six year source list mentioned above. We estimated the extension of the gamma-ray source. An extended disk with power-law spectral shape has been fitted to the data. A disk of radius 0°.32 ± 0°.03 located at R.A. = 280°.21 ± 0°.03, decl. = −4°.89 ± 0°.03 is favored over a point-like source with TS ext = 54.4. The gamma-ray source is significantly detected as an extended source with an overall TS value of 323.0. The spectral parameters are reported in Table 2. Thus, the extended gamma-ray source detected is likely the GeV counterpart of SNR Kes 73. The TS map and the radio map from the VLA Galactic Plane Survey (VGPS, Stil et al. 2006) are shown in Figure 1, left and middle panel of the corresponding row. SNR Kes 73 is clearly seen as a shell-like source in the radio map around 1E 1841−045 (Figure 1, middle panel). The gamma-ray extension detected is larger than the radio size of SNR Kes 73 and there is a radio complex which plausibly also contributes to the extended emission, leading to a larger radius than the radio shell. However, the extended gamma-ray emission peaks at SNRs Kes 73 and we propose that it is the main contributor.

In order to search for gamma-ray emission from 1E 1841−045, we need to exclude SNR Kes 73. We modeled the latter as an extended source with spatial parameters fixed at the above values and performed the likelihood analysis. 1E 1841−045 is not detected and the TS map is shown in Figure 1. By assuming a power-law spectral model, we derived 95% flux upper limits in the 0.1–1 GeV, 1–10 GeV and 0.1–10 GeV energy bands. The results are reported in Table 1.

3.1.2. 1E 2259+586

In 3FGL, a bright gamma-ray source 3FGL J2301.2−5853 is located only 0°.02 away from 1E 2259+586. In the internal six year source list, two bright gamma-ray point sources are located near 1E 2259+586, which are both spatially coincident with SNR CTB 109 (Figure 1, middle panel).

For a detailed analysis of the 1E 2259+586 region, we excluded the two sources from the spatial model. The pointlike TS map of 1E 2259+586 showed a source spatially coincident with the magnetar (Figure 1, left panel). To check for the possible extension of the gamma-ray source, we performed the likelihood analysis in a similar way as was done for 1E 1841−045. A disk of radius 0°.20 ± 0°.02 located at R.A. = 345°.46 ± 0°.02, decl. = 58°.88 ± 0°.02 is favored over a point-like source with TS ext = 23.0 (Figure 1, left panel). The gamma-ray source is significantly detected as an extended source with an overall TS value of 74.5. The spectral parameters are reported in Table 2. SNR CTB 109 is associated with 1E 2259+586, which is reported as a point-like source by Acero et al. (2016a) and an extended source by Castro et al. (2012) with a consistent extension. The TS map and the radio map from the Canadian Galactic Plane Survey (CGPS, Taylor et al. 2003) of the 1E 2259+586 region are shown in Figure 1, middle panel. SNR CTB 109 is clearly seen as a shell-like structure in the radio map around 1E 2259+586. The disk radius derived from the gamma-ray data is consistent with the radio size of SNR CTB 109. Thus, we confirm the results of Castro et al. (2012), as well as the association proposed by Acero et al. (2016a), that the extended gamma-ray source detected around 1E 2259+586 is likely the GeV counterpart of SNR CTB 109.

After we model SNR CTB 109 as an extended source with spatial parameters fixed at the above values, 1E 2259+586 is not detected (Figure 1, right panel). The 95% flux upper limits in the 0.1–1 GeV, 1–10 GeV and 0.1–10 GeV energy bands are reported in Table 1.

3.1.3. Swift J1834.9−0846 and SGR 1833−0832

Swift J1834.9−0846 is associated with SNR W41 and is in the same sky region as SGR 1833−0832. As a result, the likelihood analyses for the two sources are carried out together. SNR W41 was detected by MAGIC and H.E.S.S. at TeV energies (Aharonian et al. 2005; Albert et al. 2006) and GeV emission is expected. The point-like gamma-ray source 3FGL J1834.5−0832 from 3FGL and two point-like gamma-ray sources from the internal six year source list are located in the vicinity of the two magnetars, and are spatially coincident with SNR W41. SNR W41 was once reported as an extended gamma-ray source with a disk radius of 0°.33 by Acero et al. (2016a), and by Castro et al. (2013). Using a two-dimensional Gaussian profile, the extension of SNR W41 was reported as σ = 0°.15 by Abramowski et al. (2015). For a detailed analysis of Swift J1834.9−0846 and SGR 1833−0832 as well as exploring the possible gamma-ray extension of SNR W41, we excluded the two sources from the spatial model. The likelihood analysis of this region showed an extended gamma-ray source spatially associated with Swift J1834.9−0846 and SGR 1833−0832 (Figure 1). To check for its possible extension, we performed the likelihood analysis in a similar way as done for 1E 1841−045. A disk of
radius \(0^\circ.31 \pm 0^\circ.02\) located at R.A. = \(278^\circ.64 \pm 0^\circ.02\), decl. = \(-8^\circ.72 \pm 0^\circ.02\) is favored over a point-like source with TS\(_{\text{ext}}\) = 207.6. The gamma-ray source is significantly detected as an extended source with an overall TS value of 498.6. The spectral parameters are reported in Table 2. These are consistent with Abramowski et al. (2015) and the extension is about twice the \(\sigma\) in that paper, which is consistent considering the different extension model used—uniform disk

\[\text{Figure 1. Fermi-LAT fields of 1E 1841−045, 1E 2259+586, Swift J1834.9−0846, and SGR 1833−0832. The left column shows the possible relative TS maps in the 0.1−300 GeV range. The middle columns are the radio maps of the same region from CGPS for 1E 2259+586, and VGPS for the other sources. The right column shows the residual TS maps after modeling the gamma-ray emission of the possible relative SNRs, namely SNR Kes 73, CTB 109, and W41 for 1E 1841−045, 1E 2259+586, and Swift J1834.9−0846, respectively. The X-axis and Y-axis are R.A. and decl. referenced to J2000. The magnetars are shown with a green diamond while other sources considered in the model are shown with a white cross. The best-fit disk templates are shown with a white circle. Each source is zoomed on at the same scale and the size of disks can be directly compared. The spatial models used to produce TS maps are described in the text.} \]
model and two-dimensional Gaussian profile (Lande et al. 2012). The TS map and the radio map from VGPS around Swift J1834.9–0846 and SGR 1833–0832 are shown in Figure 1, left and middle panels. The shell-like structure of SNR W41, which is associated with Swift J1834.9–0846, is apparent in Figure 1, middle panel. No radio source is associated with SGR 1833–0832. As proposed by Acero et al. (2016a), the gamma-ray source detected is likely the GeV counterpart of SNR W41. However, there are other possible explanations for the observed extended gamma-ray emission, e.g., interaction between the SNR and cosmic rays (Frail et al. 2013; Abramowski et al. 2015), a pulsar/PWN scenario (Misanovic et al. 2011; Abramowski et al. 2015), or a magnetar/wind nebula system around Swift J1834.9–0846 (Younes et al. 2016).

We modeled SNR W41 as an extended source with spatial parameters fixed at the above values. Swift J1834.9–0846 and SGR 1833–0832 are not detected (Figure 1, right panel). The 95% flux upper limits in the 0.1–1 GeV, 1–10 GeV and 0.1–10 GeV energy bands are reported in Table 1.

3.1.4. SGR 1627–41

SGR 1627–41 is associated with SGR G337.0–00.1. This SNR was listed as “Other Detected Candidate Source” in the first Fermi-LAT SNR Catalog (Acero et al. 2016a). Its gamma-ray association was not confirmed by the spatial coincidence analysis in Acero et al. (2016a) The SNR was also observed in gamma-rays and reported by Castro et al. (2013). The point-like gamma-ray source 3FGL J1636.2–4734 from 3FGL, and two point-like gamma-ray sources from the internal 6 years source list are all in the vicinity of SGR 1627–41 and are positionally coincident with SGR G337.0–00.1 (Figure 2, middle panel). For a detailed analysis of SGR 1627–41 as well as exploring the possible gamma-ray extension of SGR G337.0–00.1, we excluded the two sources in the internal six year source list from the spatial model. The likelihood analysis of this region showed an extended gamma-ray source positionally coincident with SGR 1627–41. To check for the possible extension of the gamma-ray source, we performed the likelihood analysis. Since 3FGL J1636.2–4734 and one of the above two sources are described by a LogParabola model in 3FGL and the internal six year source list, we adopted an extended disk with LogParabola spectral shape to fit the data. A disk of radius 0.25 ± 0.01 located at R.A. = 249°00 ± 0°01, decl. = −47°54 ± 0°01 is favored over a point-like source with $TS_{\text{ext}} = 143.6$. The gamma-ray source is significantly detected as an extended source with an overall TS value of 1622.1. The spectral parameters are reported in Table 2. The TS map and the radio map from the Molonglo Galactic Plane Survey 2nd Epoch (MGPS-2, Murphy et al. 2007) are shown in Figure 2, left and middle panels. The radio complex of SNR G337.0–00.1 is clearly seen in the radio map around SGR 1627–41. The gamma-ray source detected is likely the GeV counterpart of SGR G337.0–00.1.

We modeled SGR G337.0–00.1 as an extended source with spatial parameters fixed at the above values. SGR 1627–41 is not detected (Figure 2, right panel). The 95% flux upper limits in the 0.1–1 GeV, 1–10 GeV and 0.1–10 GeV energy bands are reported in Table 1.

3.1.5. CXOU J171405.7–381031

CXOU J171405.7–381031 is associated with SNR CTB 37B while one gamma-ray point source from the internal six year source list is located within SNR CTB 37B (S3 in Figure 2, middle panel). The gamma-ray point source 3FGL J1714.5–3832 from 3FGL and one gamma-ray source from the internal six year source list (S1 in Figure 2, middle panel), which are ~0.4 away from CXOU J171405.7–381031, are positionally coincident with SGR CTB 37A. Another two point sources (S2 and S3 in Figure 2) from the internal six year source list are in the vicinity. The radio map from MGPS-2 of this region is shown in Figure 2, middle panel and the two SNRs are apparent in the radio map. Although SNR CTB 37A was once reported as a point source by Acero et al. (2016a), to exclude its influence on the analysis of CXOU J171405.7–381031, we estimated its possible extension. S1, S2 and S3 were removed from the spatial mode. To check for the possible extension of SNR CTB 37A, we performed the likelihood analysis as for the case of SGR 1627–41. Since 3FGL J1714.5–3832 and S1 were described by a LogParabola model in 3FGL and the internal six year source list respectively, we adopted an extended disk with LogParabola spectral shape to fit the data. A disk of radius 0.18 ± 0°01 located at R.A. = 258°65 ± 0°01, decl. = −38°55 ± 0°01 is favored over a point-like source with $TS_{\text{ext}} = 116.3$. The gamma-ray...
source is significantly detected as an extended source with an overall TS value of 2703.2. The spectral parameters are reported in Table 2.

The TS map of SNR CTB 37A is shown in Figure 2, left panel. SNR CTB 37A is bright and CXOU J171405.7−381031 is not seen in the TS map (Figure 2, left panel). In order to search for gamma-ray emission from CXOU J171405.7−381031, we need to exclude the gamma-ray emission from SNR CTB 37A. We modeled SNR CTB 37A as an extended source with spatial parameters fixed at the above values, included S2 and CXOU J171405.7−381031 in the spatial model, and performed the likelihood analysis. In the residual map (Figure 2, right panel), CXOU J171405.7−381031 is positionally coincident with the peak of a gamma-ray source. We checked for its possible extension but it is not significant (TSext = 8.50). By assuming a power-law spectral shape, the gtlike analysis of this gamma-ray source resulted in a TS value of 50.9 and a photon index of 1.71 ± 0.12. The flux level is estimated as 1.46 ± 0.29 × 10−11 erg cm−2 s−1 in the 0.1−300 GeV range. We explored the presence of a spectral cut-off but it is not significant (below 3σ). The results are consistent with those of Xin et al. (2016). We could not further distinguish if the source is associated with SNR CTB 37B or CXOU J171405.7−381031. By assuming a power-law spectral model, we derived 95% flux upper limits in the 0.1−1 GeV, 1−10 GeV and 0.1−10 GeV energy bands. The results are reported in Table 1.

### 3.2. Magnetars with Close-by SNRs

#### 3.2.1. SGR 0501+4516

SGR 0501+4516 is adjacent to SNR HB9. The radio map from VGPS of this region is shown in Figure 3, middle panel. The shell-like structure of SNR HB9 is clearly seen. The SNR was detected as an extended gamma-ray source with a disk radius of 1°±0.3 and a LogParabola spectral shape by Araya (2014). Two point-like gamma-ray sources from the internal six year source list are positionally coincident with SNR HB9 (S1 and S2 in Figure 3, middle panel). For a detailed analysis of SGR 0501+4516 as well as exploring the possible gamma-ray extension of SNR HB9, we excluded S1 and S2 from the spatial model. The likelihood analysis of this region
showed an extended gamma-ray source positionally coincident with SNR HB9. To check for the possible extension of the gamma-ray source, we performed the likelihood analysis as in the case of SGR 1627−41. We adopted an extended disk with LogParabola spectral shape to fit the data, as in Araya (2014). A disk of radius $1.0.32 \pm 0.05$ located at
R.A. = 75°39 ± 0°05, decl. = −46°50 ± 0°06 is favored over a point-like source with $T_{S_{ext}} = 191.8$. The gamma-ray source is significantly detected as an extended source with an overall TS value of 445.5. The spectral parameters are reported in Table 2. The gamma-ray source detected is likely the GeV counterpart of SGR HB9.

We modeled SNR HB9 as an extended source with spatial parameters fixed at the above values. SGR 0501+4516 is not detected (Figure 3, right panel). The 95% flux upper limits in the 0.1–1 GeV, 1–10 GeV and 0.1–10 GeV energy bands are reported in Table 1.

3.2.2. SGR 1900+14

SGR 1900+14 is adjacent to SNR G042.8+00.6 and SNR G043.5+00.6. The radio map from VGPS of this region is shown in Figure 3, middle panel. One point-like gamma-ray source from the internal six year source list is located only 0°07 away from SGR 1900+14 (S1 in Figure 3, middle panel). For a detailed analysis of SGR 1900+14, we excluded the source from the spatial model. The likelihood analysis of this region showed an extended gamma-ray source positionally coincident with SGR 1900+14, SNR G042.8+00.6 and SNR G043.5+00.6. To check for the possible extension of the gamma-ray source, we performed the likelihood analysis in a similar way as done for 1E 1841−045. A disk of radius 0°60 ± 0°06 located at R.A. = 287°16 ± 0°05, decl. = 9°26 ± 0°05 is favored over a point-like source with $T_{S_{ext}} = 54.7$. The gamma-ray source is significantly detected as an extended source with an overall TS value of 259.4. The spectral parameters are reported in Table 2. Besides SNR G042.8+00.6 and SNR G043.5+00.6, there are other radio sources positionally coincident with this extended gamma-ray source, which may also have contributed to the gamma-ray emission.

We modeled this new gamma-ray source as an extended source with spatial parameters fixed at the above values. SGR 1900+14 is not detected (Figure 3, right panel). The 95% flux upper limits in the 0.1–1 GeV, 1–10 GeV and 0.1–10 GeV energy bands are reported in Table 1.

3.2.3. 3XMM J185246.6+003317

3XMM J185246.6+003317 is near SNR Kes 79 which is spatially coincident with one gamma-ray source from the internal six year source list. The radio map from VGPS of this region is shown in Figure 3, middle panel. The shell-like structure of SNR Kes 79 is clearly seen. The SNR was detected as a gamma-ray source by Auchettl et al. (2014). The likelihood analysis of this region showed an extended gamma-ray source positionally coincident with SNR Kes 79 (Figure 3, left panel). For a detailed analysis of 3XMM J185246.6+003317 as well as exploring the possible gamma-ray extension of SNR Kes 79, we excluded the gamma-ray source in the internal 6 years source list from the spatial model. To check for the possible extension of the gamma-ray source, we performed the likelihood analysis in a similar way as done for 1E 1841−045. A disk of radius 0°63 ± 0°13 located at R.A. = 283°10 ± 0°03, decl. = 0°63 ± 0°14 is favored over a point-like source with $T_{S_{ext}} = 108.5$. The gamma-ray source is significantly detected as an extended source with an overall TS value of 339.5. The extension of the gamma-ray source is larger than the size of the radio shell of SNR Kes 79 (Figure 3, middle panel), which may originate from the interaction between SNR Kes 79 and the dense molecular clouds around (Auchettl et al. 2014). The spectral parameters are reported in Table 2.

We modeled this new gamma-ray source as an extended source with spatial parameters fixed at the above-quoted values. 3XMM J185246.6+003317 is not detected (Figure 3, right panel). The 95% flux upper limits in the 0.1–1 GeV, 1–10 GeV and 0.1–10 GeV energy bands are reported in Table 1.

3.3. Magnetars in Crowded Regions

3.3.1. 1RXS J170849.0−400910

1RXS J170849.0−400910 is in a crowded region on the Galactic plane. An additional point source modeled by a simple power law was added to the spatial model. The best position of the additional source was determined with pointlike as R.A. = 257°86 ± 0°04, decl. = −39°58 ± 0°04. There is no significant TS excess in the TS map. The pointlike TS value for 1RXS J170849.0−400910 is 6.6 and no clearly resolved source was seen coincident with it (Figure 4, right panel). The 95% flux upper limits in the 0.1–1 GeV, 1–10 GeV and 0.1–10 GeV energy bands are reported in Table 1. The new source yields a TS value of 197.7, a spectral index of 3.54 ± 0.01 and a flux level of 3.02 ± 0.17 × 10−11 erg cm−2 s−1.

4. TIMING ANALYSIS

Pulsar rotational phases for each gamma-ray photon that passed the selection criteria could be calculated using Tempo2 (Hobbs et al. 2006) with the Fermi plug-in (Ray et al. 2011). The significance of gamma-ray pulsations was evaluated with the weighted H-test (de Jager et al. 1989; de Jager &
Büsching 2010). However, the prerequisite is to have an available precise ephemeris for the magnetars, valid during the gamma-ray data coverage of Fermi-LAT. Because of the noisy timing nature of magnetars, valid ephemerides during the Fermi-LAT data coverage were not available for all the magnetars studied.

Adopting the ephemeris measured by Dib & Kaspi (2014) with 16 years of RXTE data, we searched for gamma-ray pulsations from 1E 1841−045, 1E 2259+586, 1RXS J170849.0−400910 and 4U 0142+614 using the H-test (Hou et al. 2014). We searched for gamma-ray pulsations for all photons below 10 GeV, exploring different values for the minimum energy (from 100 MeV to 2 GeV in a step of 100 MeV) and radius (from 0.1 to 2 in a step of 0.1) of the Fermi-LAT data. We first considered Fermi-LAT data which are contemporaneous with RXTE which operated until the end of 2011, and then extended the last available ephemeris to the rest of Fermi-LAT data. No statistically significant detection of pulsations was found. The most relevant (yet insignificant) result is obtained for the magnetar 4U 0142+614 using Fermi-LAT data with available ephemeris coverage. In the 0.4–10 GeV energy range with a data radius of 1°, we obtain 3.7σ before and 1.7σ after trials.

5. DISCUSSION

In this paper, we searched for gamma-ray emission from magnetars using six years of Fermi-LAT data, which greatly extends the results of Abdo et al. (2010a). With this larger data set, and with a total of 20 magnetars searched, we can confirm that no gamma-ray emission is detected for any of the sources studied.

Twelve out of twenty magnetars are singled out by a gtlike analysis as having TS values below 25 (Table 1). CXOU J171405.7−381031 is positionally coincident with a point source. However, we could not further distinguish if the emission originates from the magnetar or from SNR CTB 37B. For all the studied magnetars we derived the deepest upper limits to date in the 0.1–300 GeV energy range. Gamma-ray pulsations were searched for four magnetars having reliable ephemerides covering most of the Fermi-LAT data span, but no periodicity was significantly observed.

By applying an outer-gap model to magnetars, Cheng & Zhang (2001) and Zhang & Cheng (2002) predicted detectable gamma-ray emission from SGR 1900+14 and five others AXP within one year of Fermi-LAT observations. These predicted flux levels are much beyond the currently imposed upper limits. Admittedly, these models are based on a number of assumptions and parameters (see Viganò et al. 2015a for a detailed discussion). However, it would be unrealistic to suppose that these parameters (e.g., the inclination angle) should be such as to secure non-detections in all cases. This point was analyzed by Tong et al. (2010) when considering the reasons for the early non-detection of 4U 0142+61. For this particular case, even doubling the distance and using an outer gap location at 10 stellar radii or beyond, the flux would have been larger than the upper limit found (see Tong et al. 2010 for details). Takata et al. (2013) proposed a possible scenario for GeV gamma-ray emission from magnetars, in which the magnetic energy released from crust cracking could be carried into outer magnetosphere by Alfvén waves. In this case, the predicted gamma-ray flux for 1E 2259+586 is higher than the upper limits we derived. Viganò et al. (2015b) proposed an outer-gap model for gamma-ray pulsars which follows the particle dynamics to consistently compute the emission of synchro-curvature radiation. They applied this model to both the phase-averaged and phase-resolved spectra of the brightest pulsars. By fitting the model to all observed Fermi-LAT pulsar spectral data, they found a strong correlation between the accelerating electric field and the magnetic field at the light cylinder (BLC, Viganò et al. 2015c). If the correlations they found hold up to the magnetar regime (where at the light cylinder (LC), BLC ∼ 10−7−10−2 G, P ∼ 2–10 s), the accelerating electric field in the gap would be just too weak to provide particles energetic enough to emit gamma-rays. Their predictions that magnetars should not emit gamma-rays via synchro-curvature radiation is consistent with the observational results of this paper.

Analyzing the gamma-ray emission of the regions around magnetars, we confirm the significant detection of seven spatially extended gamma-ray sources, which are most likely attributed to SNRs. Four of them are believed to be associated to the spatially coincident magnetar. We have now studied them using Pass 8 data, updating their morphology and spectral parameters with respect to the 3FGL catalog (Acero et al. 2015) and to Acero et al. (2016a). The gamma-ray morphologies and luminosities of the four SNRs associated with magnetars are in line with what is expected for remnants associated with normal radio pulsars at the same age (see also Martin et al. 2014 for an X-ray comparison).

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