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SEARCH FOR GAMMA-RAY EMISSION FROM MAGNETARS WITH THE *FERMI* LARGE AREA TELESCOPE

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ABSTRACT

We report on the search for 0.1–10 GeV emission from magnetars in 17 months of *Fermi* Large Area Telescope (LAT) observations. No significant evidence for gamma-ray emission from any of the currently known magnetars is found. The most stringent upper limits to date on their persistent emission in the *Fermi* energy range are estimated between $\sim 10^{-12}$ and 10^{-10} erg s^{-1} cm^{-2}, depending on the source. We also searched for gamma-ray pulsations and possible outbursts, also with no significant detection. The upper limits derived support the presence of a cutoff at an energy below a few MeV in the persistent emission of magnetars. They also show the likely need for a revision of current models of outer-gap emission from strongly magnetized pulsars, which, in some realizations, predict detectable GeV emission from magnetars at flux levels exceeding the upper limits identified here using the *Fermi*-LAT observations.

Key words: gamma rays: stars – magnetic fields – pulsars: individual (4U 0142+614, 1E 1048.1−5937, 1E 1841−045, 1E 1547−5408, 1RXS J1708−4009, XTE J1810−197, CXOU J1647−4552, 1E 2259+586, SGR 1900+14, SGR 1806−20, SGR 1627−41, SGR 0501+4516, SGR 0418+5729) – stars: magnetars

1. INTRODUCTION

Magnetars are isolated neutron stars whose emission is thought to be powered by their magnetic energy. They are discovered either through their bursting activity (and in this case named soft gamma repeaters (SGRs); Kouveliotou et al. 1998) or by their strong persistent soft X-ray emission (then named anomalous X-ray pulsars (AXPs); Mereghetti & Stella 1995). In recent years SGRs and AXPs have been recognized as part of the magnetar class, with the discovery of many AXPs and SGRs showing common characteristics and properties (e.g., Kaspi et al. 2003; Rea et al. 2009; Mereghetti et al. 2009; Israel et al. 2010).

Their X-ray luminosities are typically 10^{33}–10^{36} erg s^{-1}. They have spin periods between 2 and 12 s and period derivatives in the 10^{-13}–10^{-11} s s^{-1}range. In most of the cases, the magnetic fields derived from their spin periods and period derivatives, assuming only magnetic dipolar losses as is usually done for normal pulsars, are inferred to be $\sim 10^{14}$–10^{15} G. These high B fields, in particular their toroidal components, impose tremendous stresses on neutron star crusts, and thereby are believed to be the ultimate energy source of magnetar emission (Duncan & Thompson 1992; Thompson & Duncan 1993). The strong soft X-ray emission can be empirically modeled with a blackbody ($kT \sim 0.3$–0.7 keV), plus a power law ($\Gamma \sim 1.5$–4; see, e.g., Mereghetti 2008 for a review), although recently more physically based models have been developed to account for their X-ray spectra (e.g., Lyutikov & Gavriil 2006; Fernandez & Thompson 2007; Rea et al. 2008; Zane et al. 2009). In the past years, magnetars have been discovered as persistent hard non-thermal X-ray sources, emitting up to ∼250 keV (e.g., Kuiper et al. 2004, Kuiper et al. 2006; Götz et al. 2006; den Hartog et al. 2008; Rea et al. 2009; Enoto et al. 2010).

Our current knowledge of their spectra at much higher energies (>0.5 MeV) is very limited. Archival studies of COMPTEL (on board the *Compton Gamma Ray Observatory*) observations were used to place upper limits on the emission of a few magnetars in the 0.75–30 MeV range, of $\sim 10^{-10}$ erg s^{-1} cm^{-2} at a 2σ level (Kuiper et al. 2006). Very poor so far is the knowledge concerning their behavior at energies >30 MeV (Heyl & Hernquist 2005), a band of interest given model predictions of measurable synchrotron/curvature emission (Cheng & Zhang 2001; Zhang & Cheng 2002).

The Large Area Telescope (LAT), the main instrument on board the *Fermi Gamma-ray Space Telescope*, launched on 2008 June 11, is the most sensitive telescope to date in the GeV energy range. We present in this Letter results of a search for emission in the GeV domain from the first 17 months of *Fermi*-LAT observations of magnetars.[55]

2. OBSERVATION AND DATA REDUCTION

The data analyzed here were taken in survey mode with the *Fermi*-LAT, from 2008 August 4 until 2010 January 1. The *Fermi*-LAT telescope is sensitive to photons with energies from about 20 MeV to more than 300 GeV and uses the pair conversion technique. The direction of an incident photon is derived by tracking the electron–positron pair in a high-resolution converter tracker, and the energy of the pair is measured with a CsI(Tl) crystal calorimeter. The *Fermi*-LAT has an on-axis effective area of 8000 cm^2, a 2.4 sr field of view, and an angular resolution of $\sim 0\overset{\circ}{.}6$ at 1 GeV (for events converting in the front section of the tracker). Furthermore, an anti-coincidence detector identifies the background of charged particles (Atwood et al. 2009).

We analyzed the data using the Fermi Science Tools `v9r15` package. Events from the "Pass 6 Diffuse" event class are selected, i.e., the event class with the greatest purity of gamma rays, having the most stringent background rejection (Atwood et al. 2009). The "Pass 6 v3 Diffuse" instrument response functions (IRFs) are applied in the analysis. For each analyzed source, we select events with energy $E > 100$ MeV in a circular region of interest (ROI) of 10° radius. The good time intervals are defined such that the ROI does not go below the gamma-ray-bright Earth limb (defined at 105° from the Zenith angle), and

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[55] We note that during the submission phase of this work another paper has been published reporting upper limits on one of the sources reported in this Letter (Şaşmaz Muş & Göğüş 2010).

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

Source	d^a kpc	log(*B*) Gauss	$\log(L_X)^a$ erg s^{-1}	$\log(L_{rot})$ erg s^{-1}	TS	0.1–10 GeV ($\Gamma = 2.5$)	0.1–1 GeV ($\Gamma = 1.5$)	1–10 GeV ($\Gamma = 3.5$)	1FGL srcs within 3°
1E 1048.1−5937	2.7	14.78	33.73	33.90	0.0	<5.3(12.0)	<3.9(7.7)	<1.7(0.7)	7
SGR 1900+14	15	14.81	35.44	34.34	0.0	<0.4(0.9)	<0.8(2.0)	<0.6(0.2)	5
SGR 0418+5729	2.0	<12.70	31.77	<29.47	2.3	<0.4(0.9)	<0.2(0.4)	<0.1(0.04)	2
SGR 1806−20	8.7	15.15	35.21	34.40	2.8	<0.6(1.4)	<0.5(0.9)	<0.12(0.05)	1
4U 0142+614	5.0	14.11	35.32	32.10	3.6	<0.9(2.0)	<0.5(0.9)	<0.3(0.11)	1
1E 1841−045	8.5	14.85	35.34	32.99	7.5	<3.0(6.0)	<6.3(13.0)	<2.4(0.92)	8
XTE J1810−197	4.0	14.46	33.58	33.60	13.1	<5.0(10.0)	<12.0(23.0)	<2.0(0.7)	7
1E 2259+586	4.0	13.76	34.25	31.70	15.6	<1.7(3.9)	<0.6(1.0)	<0.63(0.24)	2
SGR 0501+4516	5.0	14.23	34.77	33.49	16.3	<1.9(4.3)	<0.6(1.0)	<0.5(0.18)	1
1RXS J1708−4009	8.0	14.67	35.27	32.75	32.1	<10.0(20.0)	<5.0(9.0)	<9.0(4.0)	8
CXOU J1647−4552	5.0	14.20	34.41	31.89	33.7	<10.0(20.0)	<10.0(20.0)	<19.0(7.2)	7
SGR 1627−41	11	14.34	33.39	34.63	36.0	<20.0(50.0)	<20.0(30.0)	<5.0(2.0)	8
1E 1547−5408	3.9	14.32	33.49	35.00	36.2	<10.0(20.0)	<7.9(16.0)	<2.1(0.8)	6

Notes. Properties of the magnetars studied in this work ordered by the measured TS values derived from the binned analysis (for further info on the first 4 columns see Mereghetti 2008, the McGill Catalog (see footnote 57), and Rea et al. 2009, 2010 for the newly discovered SGR 0501+4516 and SGR 0418+5729, respectively). The GeV upper limits are reported at 95% confidence level (see Section 5 for details). Fluxes are in units of 10^{-11} erg s^{-1} cm^{-2}2 (or 10^{-8} photons cm^{-2} s^{-1} for numbers in brackets). The last 4 sources and 1E 1841−045 are discussed in detail in the text.
[a] Note that most of the sources have very variable X-ray luminosities, and very uncertain distances, hence those values should be taken as indicative.

that the source is always inside the LAT field of view, namely, in a cone angle of 66°.

3. LIKELIHOOD ANALYSIS AND RESULTS

Gamma-ray emission was analyzed at the positions of all the magnetars known to date, excluding yet unconfirmed candidates. Extragalactic magnetars located in the Large and Small Magellanic Clouds are also excluded due to their large distances and the difficulty of resolving them from their host galaxies (see Abdo et al. 2010a, 2010b). See Table 1 for the 13 selected magnetars.

The test statistic (TS) was employed to evaluate the significance of the gamma-ray fluxes coming from the magnetars. The TS value is used to assess the goodness of fit, and it is defined as twice the difference between the log-likelihood function maximized by adjusting all parameters of the model, with and without the source, and under the assumption of a precise knowledge of the Galactic and extragalactic diffuse emission. A TS = 25 roughly corresponds to a 4.6σ detection significance (Abdo et al. 2010d).

Binned and unbinned likelihood analyses are applied on the data, using the official tool (`gtlike`) released by the *Fermi*-LAT collaboration. The binned likelihood uses events selected in a square inscribed inside the circular ROI (see Section 2), aligned with celestial coordinates.

For each magnetar, a spectral-spatial model containing diffuse and point-like sources is created, and the parameters are obtained from a maximum likelihood fit to the data. For the Galactic diffuse emission, we use the spectral-spatial model "gll_iem_v02.fit," used by the *Fermi* Collaboration to build the First *Fermi* Source Catalog (Abdo et al. 2010d, 1FGL hereafter). The extragalactic diffuse emission was modeled as an isotropic emission using the spectrum described in the "isotropic_iem_v02.txt" file.[56] This spectrum also takes into account the residual background of charged particles in the LAT.

In the spectral-spatial model of each magnetar, we fixed its position at the localization determined by X-ray observations (in all cases with uncertainties <2″; see Mereghetti 2008 and the McGill catalog[57]), and also included all the point-like sources from the 1FGL list closer than 15°. Each of those point sources was modeled with a simple power law, with the exceptions of the pulsars closer than 3° from the magnetars, for which a power law with an exponential cutoff was used. The spectral parameters of those sources were fixed at the 1FGL values or those from the *Fermi*-LAT First Pulsar Catalog (Abdo et al. 2010c), while the flux parameters of all the point-like sources closer than 3° to the magnetar were left free in the likelihood fit (see also Table 1, last column).

We modeled the magnetar emission using power-law spectral distributions with two free parameters: the flux and the spectral index. The likelihood ratio test indicated values of TS less than 25 for most of the analyzed magnetars (see Table 1). For 1RXS J1708−4009, CXOU J1647−4552, and 1E 1547−5408, the calculated TS values were in the range 25–50, while SGR 1627−41 and 1E 1841−045 had TS > 70. The latter cases are addressed in Section 4.

For those magnetars for which X-ray outbursts were detected during the *Fermi*-LAT observing period (namely, SGR 0501+4516, SGR 0418+5729, and 1E 1547−5408; e.g., Rea et al. 2009; Esposito et al. 2010; Israel et al. 2010), we reran the analysis considering subsets of data taken one day, one week, or two weeks around the peaks of their X-ray outbursts. All TS values during those outbursts were <25.

4. SOURCES WITH HIGH-TS VALUES

Given the relatively high-TS values found in five cases by the likelihood analysis, we checked whether the X-ray positions of these magnetars are compatible with the most probable origin of the gamma-ray excesses. For this purpose, we performed a localization process similar to the one used for the 1FGL catalog, using the `pointlike` tool, which returns the TS map around each source, where the TS is calculated at any putative source position (see Figure 1 for two examples of these maps, around 1E 1547−5408 and 1E 1841−045). This tool is applied leaving

[56] All the data, software, and diffuse models used for this analysis are available from the Fermi Science Support Center: http://fermi.gsfc.nasa.gov/ssc/.

[57] www.physics.mcgill.ca/~pulsar/magnetar/main.html

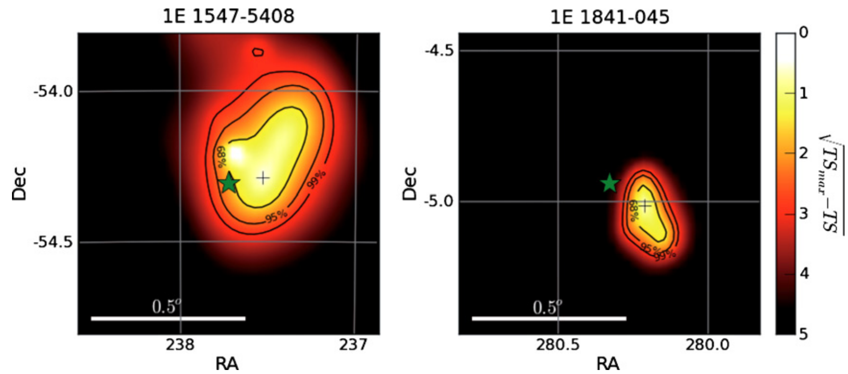

Figure 1. Test statistic maps of the *Fermi*-LAT fields of 1E 1547−5408 and 1E 1841−045 (R.A. and decl. are referenced at J2000). The green stars represent the X-ray position of each magnetar. TS_{max} is the maximum TS value inferred around the two magnetars, measured in the position labeled by the crosses. Solid lines are the positional confidence levels around the maximum TS value in each field of view. See the text for details.

as free the spectral parameters of the modeled sources within 1° of each magnetar. The results for the magnetar positions with TS > 25 are summarized below. We remember here that all of these high-TS sources are in the inner Galaxy close to the Galactic plane, where the diffuse emission is strong and highly structured, and this could affect our results.

4.1. 1E 1841−045

The `gtlike` analysis of 1E 1841−045 resulted in a high-TS value (>70). In this case the `pointlike` TS map showed a new source very close to the magnetar at an angular distance of 0°.11 (R.A. = 280°.23, decl. = −4°.99; see Figure 1, right panel). This source is not present in the 1FGL catalog, probably due to the longer time interval analyzed here (17 months versus 11 months for 1FGL). The TS value of 1E 1841−045 falls below 25 when the new source is added to the spectral-spatial model used for the likelihood analysis, and thus we find no evidence to claim the magnetar as a gamma-ray emitter.

4.2. SGR 1627−41

The `pointlike` analysis for SGR 1627−41 indicated that the position of the magnetar was not a maximum of TS when the coordinates of the modeled source were optimized in the fit. In particular, we found that the high TS derived by the `gtlike` analysis could have been caused by the presence of the rather strong unidentified source (1FGL J1636.4−47371), which lies as close as 0°.12 from the magnetar (although positionally incompatible with it). If the spectral parameters of the modeled 1FGL sources are held fixed at their values in the 1FGL catalog, SGR 1627−41 ends up having a TS ∼ 36. This is what is reported in Table 1. While this is still greater than 25, the flatness of the TS map around this source suggests that in this region the diffuse Galactic emission could be underestimated by the model adopted in the likelihood analysis.

4.3. 1RXS J1708−4009 and CXOU J1647−4552

The `gtlike` analyses of these two magnetars resulted in TS values of ∼30 for both sources. For each source, we performed a `pointlike` analysis which in both cases indicated that the positions of the two magnetars were not a maximum of TS when the coordinates of the modeled source were optimized in the fit. We cannot exclude that the likelihood excesses of 1RXS J1708−4009 and CXOU J1647−4552 are caused by the uncertainties of the Galactic diffuse model.

4.4. 1E 1547−5408

1E 1547−5408 is the only source for which the TS map calculated by `pointlike` indicated that the position of the magnetar was indeed consistent with a local maximum of TS (see Figure 1, left panel). In particular, 1E 1547−5408 has a TS ∼ 35, and it is observed inside the 95% positional error contour around the TS_{max} of the field. With the current *Fermi* observations a firm association between this excess and 1E 1547−5408 can not be made. Furthermore, we found that the TS of 1E 1547−5408 falls below 20 if the level of the Galactic diffuse emission is increased by only 2%

5. UPPER LIMITS EVALUATION

Before starting with the upper limit determination, we note that for all but one magnetar, the local maximum of TS was not coincident with the magnetar position. Furthermore, by increasing the level of the Galactic diffuse emission by 2%–4%, all of the TS values determined in Section 3 would decrease below 20. These percentages are well inside the systematics of the assumed Galactic diffuse emission model (see the cases of the supernova remnants W51C and W49, and Section 4.7 of the 1FGL catalog; Abdo et al. 2009, 2010b, 2010e).

The discovery of GeV gamma rays from magnetars would have major implications, hence would require very strong evidence. The evidence so far does not seem to reach more than the circumstantial level, and while the *Fermi*-LAT exposure continues to accumulate on these sources, we find it appropriate for the time being to report only upper limits.

The upper limits are evaluated by applying the binned likelihood analysis and using the spectral-spatial models described above. We derived 95% flux upper limits by fitting a point source at the X-ray magnetar position, for which we increase the flux until the maximum likelihood decreases by 2.71/2 in logarithm.

In the 0.1–10 GeV energy range, we fix the photon index value of the magnetars to 2.5, which is the mean of the photon indices obtained by the previous likelihood analyses. The other two upper limits are evaluated using spectral index values that mimic a cutoff in the spectrum at ∼1 GeV, as common in pulsar spectra. Accordingly, in the range 0.1–1 GeV we fix the spectral index to 1.5, while for 1–10 GeV it is set as 3.5.

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. We estimated the effect of these systematics by repeating the upper limit analysis using modified IRFs that bracket the "Pass

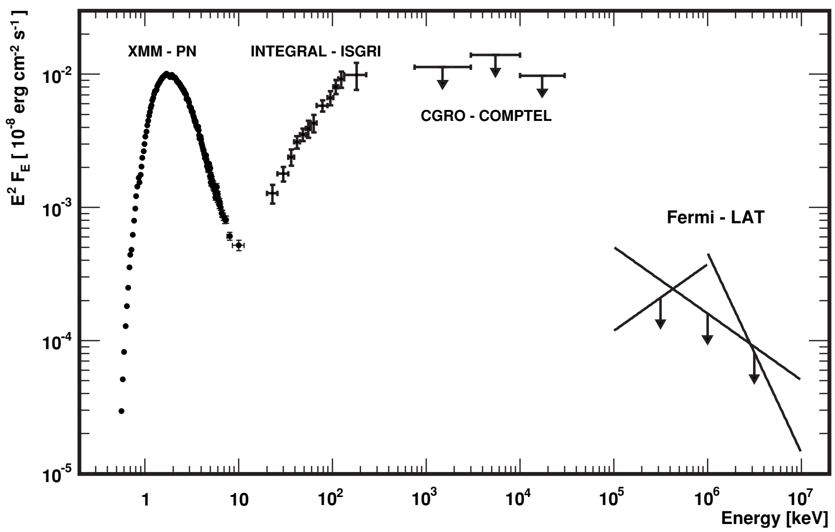

Figure 2. Multi-band E^2F_E spectrum of 4U 0142+614. The 0.1–200 keV data are from *XMM-Newton*-PN and *INTEGRAL*-ISGRI (Rea et al. 2007a; den Hartog et al. 2008; Gonzalez et al. 2010), on which we overplot the 2σ COMPTEL upper limits (den Hartog et al. 2006; Kuiper et al. 2006) and the *Fermi*-LAT limit (this work) with the assumed power-law spectrum with photon index values of 2.5, 1.5, and 3.5 in the 0.1–10 GeV, 0.1–1 GeV, and 1–10 GeV bands, respectively (see also Table 1).

6 v3 Diffuse" effective areas and changing the normalization of the Galactic diffuse model artificially by ±6%. The results of this analysis are reported in Table 1.

6. TIMING ANALYSIS

A timing analysis was performed for each of the 13 magnetars studied in this work. With this aim we used the X-ray data available for these objects to build their ephemerides to fold the *Fermi*-LAT data, or we searched around their X-ray periods when a long baseline ephemeris could not be derived. In particular, using *RXTE* and *Swift*-XRT data, ephemerides[58] have been derived for 4U 0142+614, 1E 2259+586, 1E 1048.1−5937, 1RXS J1708 −4009, 1E 1841−045, 1E 1547−5408, and SGR 0501+4516 (R. Dib et al. 2011, in preparation; Israel et al. 2010; F. Bernardini et al. 2011, in preparation; Rea et al. 2009; N. Rea et al. 2011, in preparation). For each of the other magnetars, an ephemeris valid throughout the 17 months of *Fermi*-LAT observations is not derivable either given the paucity of X-ray observations or because the source is too dim to have long-term measurements of its spin period. For these we searched directly in the gamma-ray data, performing a semi-blind search around plausible values of spin period and its derivative (see Mereghetti 2008). With the help of PRESTO software (Ransom 2001), we also tried to improve the signal including trials for the second derivative of the period. No significant signal has been detected either searching in *Fermi*-LAT data around the X-ray period, or, when possible, folding at the X-ray ephemeris derived from current X-ray monitoring observations.

7. DISCUSSION

In this Letter, we searched for GeV emission from magnetars using the most sensitive data to date. We did not find evidence beyond reasonable doubt that would allow us to claim the detection of any of these magnetars. In a few cases, putative detections were marked for further studies, but they are not significant enough to claim a new population of gamma-ray emitters.

For all of the studied magnetars we calculated the deepest upper limits derived to date in the 0.1–10 GeV energy range. In Figure 2, we show the 0.1 keV–10 GeV multi-band spectrum of 4U 0142+614, the persistent magnetar having the brightest emission and steepest spectral decomposition in the hard X-ray band. Comparing the *Fermi*-LAT upper limits to the hard X-ray measured fluxes for all the studied magnetars, it is clear that the spectral energy distribution of these objects should necessarily have a cutoff below the MeV band, as already pointed out for a few sources by COMPTEL observations (den Hartog et al. 2006; Kuiper et al. 2006).

In particular, fitting a log-parabolic functions to the hard X-ray spectrum of 4U 0142+614 (Kuiper et al. 2006; Rea et al. 2007b; den Hartog et al. 2008) as an example resulted in a peak energy of 279^{+65}_{-41} keV (den Hartog et al. 2008). This kind of spectral model has been successfully applied to many pulsars such as the Crab or Vela (Kuiper et al. 2001; Massaro et al. 2006a, 2006b; Rea et al. 2007b). Such log-parabolic spectra can be approximately obtained when relativistic electrons are accelerated by some mechanism and competitively cool via synchrotron or by inverse Compton scattering losses. The narrow energy range of each log-parabolic component might then reflect a tight balance between cooling and acceleration in a relatively confined emission locale.

On the other hand, in some cases the hard X-ray tail at >10 keV can be equally well modeled with a flat power law with an exponential cutoff (e.g., den Hartog et al. 2007, 2008) as opposed to a log-parabolic form. One possibility suggested by this is that resonant inverse Compton scattering by a population of highly relativistic electrons energized at altitudes below around 10 stellar radii may provide this hard X-ray component of magnetars (see Thompson & Beloborodov 2005; Baring & Harding 2007; Nobili et al. 2008), probably using seed thermal photons emanating from the stellar surface. In this scenario, the *Fermi*-LAT and COMPTEL spectroscopic constraints, implying a turnover around 200–500 keV, profoundly limit a combination

[58] Only in a few cases a single ephemeris could be derived over the entire time baseline, while in other cases 4–5 different ephemerides were needed to cover the whole *Fermi*-LAT data span.

of the Lorentz factor of the radiating electrons and the typical viewing angle of the observer (Baring & Harding 2007). Accordingly, phase-resolved spectroscopy will provide important diagnostics on more refined models of such a scenario (see, e.g., den Hartog et al. 2008). Note that Trümper et al. (2010) recently invoked a bulk-Comptonization, fallback disk model as an alternative, non-magnetar explanation for these tails.

The low *Fermi*-LAT upper bounds provide interesting constraints on postulated magnetar synchrotron/curvature emission from high altitudes. The emerging paradigm for young pulsars that are bright in the 100 MeV–10 GeV energy range (Abdo et al. 2010c) is that they emit due to acceleration in a slot-gap or outer-gap potential not far from their light cylinders. Much earlier, Cheng & Zhang (2001) and Zhang & Cheng (2002) proposed an outer-gap model for magnetar emission above 30 MeV, mediated by pairs created at high altitudes in collisions between X-rays originating on or near the surface, and GeV-band primary photons from electrons accelerated in the gap. Given the nominal *Fermi*-LAT sensitivity, their model predicted that SGR 1900+14 and five AXPs (see Figure 5 of Cheng & Zhang 2001) would have been observable within a year with fluxes of the order of 10^{-7} to 10^{-9} photons cm^{-2} s^{-1}, depending on the assumed parameters. However, *Fermi*-LAT does not detect any of these magnetars in 17 months of data. This strong observational diagnostic necessarily forces a revision of the parameter space applicable for the viability of their outer-gap model to each magnetar.

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