Fermi LAT Observations of Magnetars

A.K.H. Kong[1], J. Takata[2], J.H.K. Wu[1], K.S. Cheng[2], P.H.T. Tam[1], C.Y. Hui[3], on behalf of the Fermi Asian Network

[1] National Tsing Hua University, Taiwan
[2] The University of Hong Kong, Hong Kong
[3] Chungnam National University, Korea

1 Introduction

Soft Gamma-ray Repeaters and Anomalous X-ray Pulsars (AXPs) have been discussed in terms of "magnetar" model, in which the activities of the neutron star are powered by the dissipation of the extremely strong magnetic field (Thompson & Duncan 1995; Thompson, Lyutikov & Kulkarni 2002; Woods & Thompson 2006; Mereghetti 2008). The magnetar's emissions mainly appear in the X-ray bands, which are described by the blackbody component (with hard tail) below 10 keV plus a hard power law component above 10 keV (Kuiper et al. 2006). The power law components are often explained by the resonant Compton scattering process of the mildly relativistic electrons and/or positrons below 10 keV (Fernández & Thompson 2007; Rea et al. 2008) and of the relativistic pairs above 10 keV (Beloborodov & Thompson 2007; Baring & Harding 2007; Beloborodov 2013), respectively.

Although no pulsed GeV emissions from the magnetars have been confirmed, it has not been conclusive that magnetars are intrinsically dark in the GeV radiation, or present sensitivity of the *Fermi* telescope is not sufficient enough to detect any pulsed GeV emission from magnetars. Recently, GeV γ-rays from the supernova remnant (SNR) CTB 109, which is associated with the AXP 1E 2259+586, have been found with *Fermi* LAT (Castro et al. 2012). Although the emissions from SNR CTB 109 has been suggested (Castro et al. 2012), the origin has not been confirmed yet. Because future *Fermi* observations will allow us a much deeper search for the GeV emissions from magnetars, it is worthwhile to consider different physical processes of GeV γ-ray emissions in the magnetosphere of magnetars and plan a taylor-made observing strategy to look for their GeV γ-rays.

2 Theory

2.1 Previous studies

The non-thermal physical processes in the vicinity of the stellar surface have been discussed to study the X-ray emissions from magnetars. The observed power of the X-ray emissions exceeds the spin down power of the magnetar, suggesting magnetar's activities are powered by dissipation of the magnetic field rather than by loss of the rotation energy. Beloborodov & Thompson (2007) proposed two possible processes for the non-thermal X-ray emission associated with the dissipation of the magnetic field: (1) the bremsstrahlung process from a thin turbulent layer of the star's surface, which is heated by the current carriers, or (2) the synchrotron radiation process from electron and positron pairs produced at a height of 100 km from the stellar surface. In the first case, the emission can extend up to ~ 100 keV, and in the second case, the spectrum has a peak at ~ 1 MeV. Baring and Harding (2007) argued that resonant Compton scattering process may play an important role in the production of hard X-ray emissions. However, the emission mechanism of the hard non-thermal component has not been conclusive up to now. The previous models have not predicted the γ-ray emissions (> 100MeV) from magnetars, because the γ-rays emitted near the stellar surface are converted into pairs by the magnetic pair-creation process and/or photon-photon pair-creation process.

The ultra-strong surface magnetic field and the strong X-ray fields of the magnetars make γ-rays difficult to escape from the pair-creation processes. We can roughly estimate the critical radius below which the emitted γ-rays are virtually impossible to be observed (Takata et al. 2013). For $\sim$GeV photons, for example, the mean-free path of the magnetic pair-creation process becomes order of unity at the radial distance $r_m \sim 3 \times 10^7 (E/3\mathrm{GeV})^{1/3}$cm, implying GeV photons emitted below r_m is totally absorbed. For the photon-photon pair-creation process, we can see that the mean free path of the $\sim$GeV photons is larger than unity within the radial distance $r_p \sim 7 \times 10^7 L_{X,35}$cm, where $L_{X,35}$ is the luminosity of the background X-ray field in units of 10^{35}erg/s. As a result, the GeV photons cannot escape from the pair-creation process if they are produced below the critical distance $r_c \sim 5 \times 10^7$cm.

It has been argued that the rotation powered activities of the magnetars can produce γ-rays from e.g. the outer gap accelerator (Cheng & Zhang, 2001). However, because the temperature of the surface X-ray emissions of magnetars is $kT \sim 0.5$keV, which is much higher than the typical surface temperature $kT \sim 0.1$ keV of young pulsars, the size of the outer gap, and the resultant power of the γ-ray emissions will be relatively smaller than those of the canonical γ-ray pulsars, indicating less possibility for the detection of the pulsed γ-ray emissions from the outer gap of magnetars.

2.2 γ-ray emission model

One possible scenario producing observable γ-rays from magnetars is that the Alfvén waves carries the released magnetic energy into outer magnetosphere $r > r_c$ and the decay of the Alfvén wave produces the relativistic particles, which can emit γ-rays (Takata et al. 2013). It can be thought that the X-ray outburst of magnetar is caused by the crust cracking of the strong magnetic field, and the Alfvén wave is excited to carry the released energy into the magnetosphere. If location of the cracking is close to the magnetic pole, part of the released energy can be carried by the Alfvén waves that propagate into the outer magnetosphere $r \geq r_c \sim 5 \times 10^7$ cm, where the γ-rays can escape from the pair-creation processes.

The amplitude of the magnetic field corresponding to the Alfvén wave near the stellar surface becomes

$$\delta B(R_s) \sim 5 \times 10^{10} \left(\frac{E_{tot}}{10^{42}\mathrm{erg}} \right)^{1/2} \mathrm{G}, \tag{1}$$

where E_{tot} is the typical released energy at the X-ray outburst. As the Alfvén wave propagates from the stellar surface into outer magnetosphere, the amplitude will evolve as $\delta B(r) \propto A^{-1/2}(r)$, where $A(r)$ is the cross section of the oscillating magnetic flux tube, while the background dipole field is proportional to $B_d(r) \propto A^{-1}(r)$. Then we find that the fractional perturbation of the magnetic field becomes an order of unity at the radial distance $r \sim 10^8[\delta B(R_s))/10^{-3}B_d(R_s)]^{-2/3}$ cm. Because the induced electric field is same order of magnitude as the perturbed magnetic field, $\delta E \sim \delta B$, the total electric field is of order of the magnetic field $|E| \sim |B|$, where conversion from the electromagnetic energy into the particles energy could be possible (Beskin & Rafikov 2000). When the nonlinear term becomes to be important, by whatever process, a substantial part of the wave energy is probably converted into electron/positron energy, which in turn radiate the GeV γ-rays.

2.3 Radiation characteristics

Based on the present scenario, the perturbation of the magnetic field lines can induce the electric potential of

$$\delta\Phi_p \sim \delta\ell \times \delta B = 1.5 \times 10^{15} \left(\frac{\delta B(R_s)/B_{\mathrm{d}}(R_s)}{10^{-3}} \right) \left(\frac{\delta B(R_s)}{5 \cdot 10^{10}\mathrm{G}} \right) \left(\frac{\ell}{10^5\mathrm{cm}} \right) \mathrm{Volts}, \tag{2}$$

where ℓ is the size of the cracked region and $\delta\ell \sim \delta B(R_s)\ell/B_{\mathrm{d}} \sim 100$cm is the displacement of footprints of the oscillating magnetic lines. The typical Lorentz factor will be characterized by

$$\Gamma_{max} \sim 3 \times 10^7 \left(\frac{R_c}{10^8\mathrm{cm}} \right)^{1/4} \left(\frac{L}{R_c} \right)^{-1/4} \left(\frac{\Phi_p}{10^{15}\mathrm{Volt}} \right)^{1/4} \tag{3}$$

where R_c is the curvature radius of the magnetic field line and we used typical electric field $E_{||} = \delta\Phi_p/L$ with L being the arc length of the acceleration region along the magnetic field line. We can see that the typical energy of the curvature photons becomes several GeV, that is,

$$E_c = \frac{3}{4\pi} \frac{hc\Gamma^3}{R_c} \sim 8 \left(\frac{\Gamma}{3 \cdot 10^7} \right)^3 \left(\frac{R_c}{10^8\mathrm{cm}} \right)^{-1} \mathrm{GeV}. \tag{4}$$

The maximum radiation power is

$$L_{\mathrm{r}} \sim \delta\Phi_p \times I \sim 4 \times 10^{35} \left(\frac{\Omega}{1\mathrm{Hz}} \right) \left(\frac{\delta B(R_{\mathrm{s}})}{5 \cdot 10^{10}\mathrm{G}} \right)^2 \left(\frac{\ell}{10^5\mathrm{cm}} \right)^3 \left(\frac{I}{I_{GJ}} \right) \mathrm{erg\ s}^{-1}, \tag{5}$$

where I is the total current along the oscillating flux tube and $I_{GJ} \sim i_{GJ}\ell^2$ with $i_{GJ} = \Omega B/2\pi$ being so-called Goldreich-Julian current. The emission will last for a temporal scale of years, $\tau = E_{tot}/L_{\mathrm{r}} \sim 10^{7-8}$s after an X-ray outburst.

There are two distinct types of magnetar's bursts, which were named Type A and Type B (Woods et al. 2005). Type A bursts are frequently seen in SGR bursts, and the energy emitted during primary burst peak is larger than the tail energy. In Type B bursts, on the other hands, energy of primary burst peak is smaller than the tail energy. Woods et al. (2005) speculated that Type A and Type B bursts are triggered by magnetospheric reconnection (Lyutikov 2003) and by crust fractures (Thompson & Duncan 1995), respectively. Based on the present scenario, therefore, we expect γ-ray emissions could be observed after Type B bursts.

For example, the X-ray outburst AXP 1E 2259+586 in 2002 consisted of a rapidly decay emission in the first few hours with a released energy of $\sim 10^{38}$ergs and a slow decay emission lasting for several years with a released energy of $> 10^{41}$ ergs (Woods et al. 2004; Zhu et al. 2008), suggesting a Type B burst. We expect that during a rapidly decay phase, a strong X-ray field prevents γ-rays to escape from the pair-creation process, and hence no γ-ray emissions were observed. The γ-rays, however, will be observed during the slow decay phase of the X-ray emissions.

The GeV γ-ray emissions in the direction of CTB 109, which is associated with the AXP 1E 22459+586, were founded in the $Fermi$ LAT data (Castro et al. 2012). Although an origin from the SNR has been suggested, the possibility that the emission from the AXP 1E 22459+586 has not been ruled out yet. We present here the predicted spectrum in wide energy band using the parameters of the AXP 1E 2259+586 ($\Omega \sim 0.9\mathrm{s}^{-1}$ and $B_d(R_s) \sim 10^{14}$G). We can see in Figure 1 that the observed flux level below 10 GeV can be explained by the present scenario. Above 10 GeV, the model flux is weaker than the observations, and hence the emissions from SNR likely dominate the magnetospheric emissions.

3 Discussion

The pulsed GeV γ-ray radiation from the magnetars have not been reported yet, although the predicted luminosity $L_\gamma \sim 10^{35}$ erg s^{-1} may be large enough to detect pulsed GeV γ-rays by the $Fermi$ telescope. However, several reasons can be raised to explain the non-detection of the pulsed GeV emissions from magnetars. First, since magnetars are in general located at the Galactic plane and inside SNRs, the background radiation (e.g. emissions from SNR shock) may prevent the detection of the pulsed radiation. Second, magnetars have shown frequent glitches that are sudden changes in frequency and/or frequency derivative (İçdem et al. 2012). Hence the timing parameters of the magnetars are very unstable, which makes even harder to detect the pulsed period in the $Fermi$ data.

We note that the typical luminosity of GeV radiation of SNRs is on order of 10^{34-35} erg s^{-1}, which is same order of magnitude predicted by the present magnetosphereic emission model. Hence, it would be possible that the GeV emissions in the direction of magnetars are composed of the emissions from SNRs and magnetospheres. The pulsed radiation predicted by the present scenario will change its luminosity level $L_\gamma \sim 10^{34-35}$erg s^{-1} at a temporal scale of years after the energy

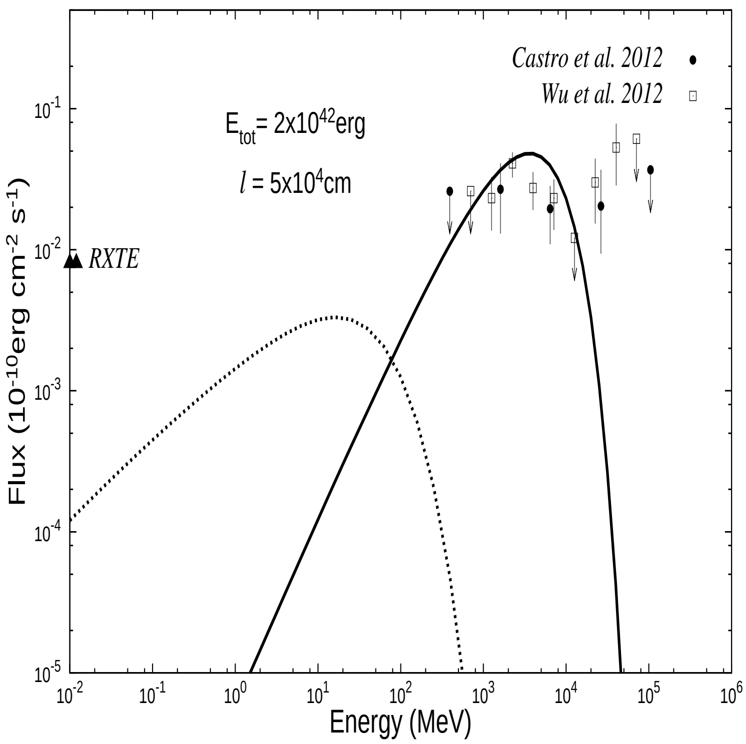

Figure 1: The spectrum of AXP 1E 2259+586. The solid line is the predicted spectrum of the curvature radiation process at $r > 5 \times 10^7$ cm. The results are for $E_{tot} = 2\times10^{42}$erg and $\ell = 5\times10^4$cm. The dotted line is spectrum of the synchrotron radiation from the first generation of the pairs produced 10^7cm $\leq r \leq 5 \times 10^7$cm, if all curvature photons above 1GeV (dashed line) are absorbed by magnetic field. The data are taken from Castro et al. (2012) and from Wu et al. (2012) for the $Fermi$ and from Kuiper et al. (2006) for the $RXTE$, respectively.

injection into the magnetosphere, while the SNR's emission will be stable. Hence, a temporal behavior of the observed GeV emissions will discriminate between the two components.

4 Observing Strategy and Feasibility

Based on above arguments, part of the outburst energy of magnetars will be released in exciting Alfven waves, which can accelerate electrons/positrons to relativistic energy (Takata et al. 2013). Multi-GeV gamma-rays will be emitted by these electrons/positrons through curvature radiation process. However, gamma-rays cannot escape from the photon-photon pair creation until the X-ray luminosity emitted from regions near the stellar surface decreases below 10^{35}erg s^{-1}. Furthermore the amplitude of Alfven waves will gradually decrease due to various dissipation processes with a time scale of months. The most optimal observed period of such transient gamma-ray emission events could be less than several months. Given the fact that all magnetars are quite far away and it is more desirable to have a modified survey observation after the magnetar outbursts in order to collect sufficient number of photons in a month or so.

As we mentioned above, the gamma-rays can only be seen when the X-ray luminosity is below 10^{35}erg s^{-1}, the proposed observation does not require a quick response. Currently, there are several all-sky X-ray monitor instruments (such as *MAXI* and *Swift*/BAT) that are useful for detecting X-ray outbursts from magnetars; *Fermi*/GBM is also possible to detect any hard X-rays from magnetars. Once an outburst is confirmed, there must have regular observations across the wavelengths proposed by other observers to follow the outbursts. If there is no scheduled X-ray observations (e.g. *Swift*/XRT), we will propose a TOO monitoring program. The key of our proposed *Fermi*/LAT observation is to wait until the X-ray luminosity is below 10^{35}erg s^{-1}. A typical magnetar's outburst lasts for about a month and therefore the *Fermi* team should have sufficient time to prepare a trigger. Once the X-ray luminosity is below 10^{35}erg s^{-1}, we will trigger a modified survey LAT observation.

In order to plan the observing strategy, we first estimate the photon flux from a magnetar. The characteristic photon flux from a magnetar is estimated as follows:

$$F = L_\gamma/4\pi d^2(3\mathrm{GeV}) \tag{6}$$

$$L_\gamma < L_x \sim 10^{35}\mathrm{erg\ s}^{-1} \tag{7}$$

$$\begin{aligned} F &= 10^{35}/[4\pi(3\mathrm{kpc})^2(3\mathrm{GeV})] \\ &= 3\times10^{-8} ph/cm^2/s(L_\gamma/10^{35}\mathrm{erg\ s}^{-1})/(d/3\mathrm{kpc})^2 \end{aligned} \tag{8}$$

From a catalog of magnetars[1], we performed a modified survey observation simulation. For each of the magnetar candidates, we point the LAT at the magnetar's

[1] http://www.physics.mcgill.ca/∼pulsar/magnetar/main.html

Table 1: Target List

Source	Distance (kpc)	3 GeV Photon	Target exposure over survey	Observation Efficiency[1]
4U 0142+61	3.6	208	2.27	0.83
1E 1048.1-5937	2.7	370	2.40	0.86
1E 1547.0-5408	4.5	133	2.15	0.85
CXOU J164710.2-455216	3.9	178	2.29	0.88
1RXS J170849.0-400910	3.8	187	2.31	0.90
XTE J1810-197	3.5	220	2.66	0.94
1E 2259+586	3.2	264	2.30	0.86

[1] Mean exposure of modified survey mode over survey mode

position with a 5 degree offset from the RA. We then make a transition into a 50 degree rocking survey when the magnetar is 10 degrees from Earth occultation, and slew back to the target when it is exiting 10 degrees from Earth occultation. EAA is set to 30 degrees, so the LAT boresight will track to within 30 degrees of Earth limb and then hold steady until target reaches 10 degrees from the Earth limb. For each candidate, we compute the number of 3 GeV photons according to Equation 8, the observation efficiency and exposure, and compare with the survey mode (see Table 1).

First of all, we can eliminate magnetars with distances greater than 8 kpc because even with a 60-day modified survey observation, there are no more than 70 photons and we therefore exclude them in our target list. In Table 1, we list our proposed targets. If any one of them goes into an outburst, we will trigger the LAT observation with the modified survey mode when the X-ray luminosity is below 10^{35}erg s^{-1}. Here we propose to have a 30-day modified survey that allows us to obtain 100–300 photons from the magnetar. This is only a lower limit since we only calculate for 3 GeV photons. The exposure of the target increases by a factor of 2.2–2.7 comparing to the survey mode. The percentage loss in efficiency between the modified survey mode and survey mode is 6–17%. We will work with the *Fermi* team to fine-tune the observing parameters in order to optimize the scientific outputs when we know exactly which magnetar is in outburst. With this observing strategy, we are hoping to detect the gamma-ray emission from a magnetar for the first time.

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