

NON-DETECTION IN A *FERMI*/LAT OBSERVATION OF AXP 4U 0142+61: MAGNETARS?

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ABSTRACT

Significant research in compact stars is currently focused on two kinds of enigmatic sources: anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs). Although AXPs and SGRs are popularly thought to be magnetars, other models (e.g., the accretion model) for understanding the observations can still not be ruled out. It is worth noting that a non-detection in a *Fermi*/LAT observation of AXP 4U 0142+61 has been reported recently by Sasmaz Mus & Gogus. We propose here that *Fermi*/LAT observations may distinguish between the magnetar model and the accretion model for AXPs and SGRs. We explain how this null observation of AXP 4U 0142+61 favors the accretion model. Future *Fermi*/LAT observations of AXP 1E 1547.0–5408 and AXP 1E 1048.1–5937 are highly recommended.

Key words: pulsars: general – pulsars: individual (AXP 4U 0142+61) – stars: magnetic field – stars: neutron

Online-only material: color figures

1. INTRODUCTION

Anomalous X-ray pulsars (AXPs) are pulsar-like objects, whose X-ray luminosities are in excess of their rotational energy losses while they show no binary signature, thus acquiring the name “anomalous” X-ray pulsars (Mereghetti 2008). AXPs, along with soft gamma-ray repeaters (SGRs), are candidate magnetars, neutron stars powered by strong magnetic field decay (Duncan & Thompson 1992; Paczynski 1992). Alternative explanations for AXPs and SGRs involve a normal neutron star accreting from a supernova fallback disk (Alpar 2001; Chatterjee et al. 2000). It is then a very fundamental question to determine whether AXPs and SGRs are magnetars or accretion-powered systems. To finally solve this problem is not only helpful to understand the equation of state at supra-nuclear densities, but also very meaningful to explain high-energy astrophysical phenomena (Xu 2007).

The magnetar model is prevailing in explaining bursts of AXPs and SGRs (Paczynski 1992; Thompson & Duncan 1995). However, bursting behavior in the accretion model is not absolutely impossible (Rothschild et al. 2002; Xu et al. 2006). It is also possible that the magnetar field ($\sim 10^{14}$ – 10^{15} G) responsible for bursts is in higher multipole form while a normal dipole component ($\sim 10^{12}$ – 10^{13} G) interacts with the fallback disk (Eksi & Alpar 2003; Ertan et al. 2007). Observations in the optical/IR band are informative, e.g., a debris disk is found around AXP 4U 0142+61 (Wang et al. 2006). The optical/IR observation of 4U 0142+61 can be explained uniformly in an accretion fallback disk model (Ertan & Cheng 2004; Ertan et al. 2007). However, if the disk is passive, a fallback disk is also compatible with the magnetar scenario (Wang et al. 2006). Therefore, observations at other wavelengths are very necessary to understand the real nature of AXPs and SGRs, especially in gamma rays.

The outer gap model (e.g., Cheng et al. 1986) is very successful, and high-energy gamma-ray emissions of AXPs have been calculated and predicted by Cheng & Zhang (2001) in the magnetar domain, using the thick outer gap model (Zhang & Cheng 1997). The detailed calculations of Cheng & Zhang (2001) predicted that *Fermi*/LAT should be able to detect

gamma-ray emission of AXPs, including 4U 0142+61, if they are magnetars. However, a recent *Fermi*/LAT observation of 4U 0142+61 has been reported, which shows no detection (Sasmaz Mus & Gogus 2010). Then there seems a conflict between theory and observation. While adopting the thick outer gap model (Zhang & Cheng 1997), simple calculations show that AXPs are not high-energy gamma-ray emitters if they are normal neutron stars accreting from fallback disks. We suggest that *Fermi*/LAT observation of AXPs and SGRs can be applied to distinguish between the magnetar model and the accretion model. The non-detection of 4U 0142+61 may prefer the accretion model.

In Section 2, we compare theoretical predictions from the magnetar model with *Fermi*/LAT observation of AXP 4U 0142+61. Discussions are presented in Section 3.

2. THEORETICAL CALCULATIONS IN THE MAGNETAR MODEL

Zhang & Cheng (1997) developed the thick outer gap model for long period pulsars. The typical Lorentz factor is determined by equaling energy loss and gain. The γ - γ pair production threshold determines the size of the outer gap self-consistently. If the X-ray photons are provided by surface thermal emission, the size of the outer gap is (Equation (24) in Zhang & Cheng 1997)

$$f = 4.5P^{7/6} B_{12}^{-1/2} T_6^{-2/3} R_6^{-3/2}, \quad (1)$$

where P is the pulsar rotation period, B_{12} is the stellar magnetic field in units of 10^{12} G, T_6 is the surface temperature in units of 10^6 K, and R_6 is the stellar radius in units of 10^6 cm. Here, f should be less than one for outer gap to exist. In the magnetar model for AXPs and SGRs, typical parameters are $P = 7$ s, $B = 5 \times 10^{14}$ G, and $T = 0.5$ keV. The stellar radius is chosen as $R = 12$ km, which is moderate for realistic equations of state (Lattimer & Prakash 2007, their Figure 6; in Cheng & Zhang 2001 the stellar radius is chosen as 15 km). The corresponding outer gap size is then $f = 0.46$, which means that if AXPs and SGRs are magnetars, they should be high-energy gamma-ray emitters. On the other hand, if AXPs and SGRs are normal neutron stars whose (dipolar) magnetic fields are 10^{12} – 10^{13} G (Alpar 2001; Chatterjee et al. 2000), the corresponding outer

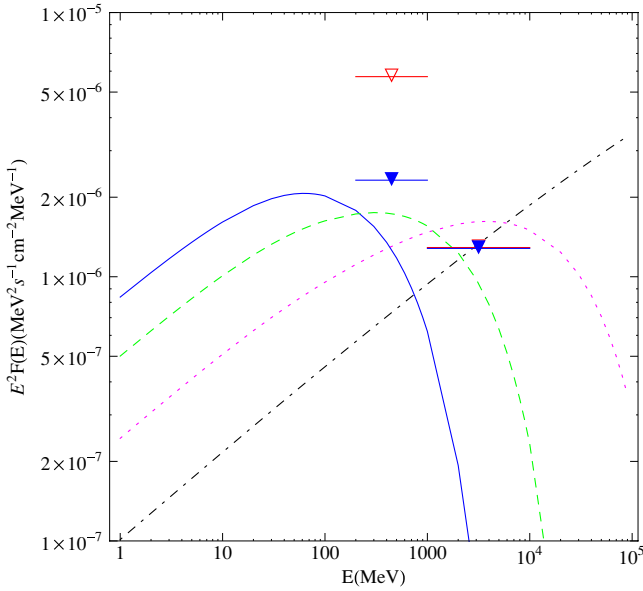


Figure 1. *Fermi*/LAT upper limits of AXP 4U 0142+61 compared with outer gap calculations in the magnetar domain. The solid, dashed, and dotted lines are for inclination angle 45° , 60° , 75° , respectively (Zhang & Cheng 1997; Cheng & Zhang 2001). The dot-dashed line takes into consideration that the inner boundary of outer gap may extend to 10 stellar radii (Hirotani et al. 2003; Hirotani & Shibata 2001). The empty down triangle and filled down triangle are *Fermi*/LAT upper limits (0.2–1 GeV and 1–10 GeV) from 2° and 15° extraction region, respectively (Sasmaz Mus & Gogus 2010). The upper limits in 1–10 GeV are nearly coincide.

(A color version of this figure is available in the online journal.)

gap size is $f = 3$ –10. Therefore, if AXPs and SGRs are normal neutron stars accreting from fallback disks, they will not radiate high-energy gamma rays.³ Thus, *Fermi*/LAT observations of AXPs and SGRs can be helpful to distinguish between the magnetar model and the accretion model.

Sasmaz Mus & Gogus (2010) reported *Fermi*/LAT observation of AXP 4U 0142+61. With an exposure time of 31.7 Ms, they find no detection of high-energy gamma-ray emission from 4U 0142+61 in both 0.2–1 GeV and 1–10 GeV band. Observational upper limits and theoretical calculations in the magnetar model are shown in Figure 1. For 4U 0142+61, its parameters are $P = 8.688$ s, $B = 2.6 \times 10^{14}$ G, and $T = 0.395$ keV (from the McGill AXP/SGR catalog⁴). The magnetic field is calculated from $B = 6.4 \times 10^{19} \sqrt{P\dot{P}}$, which is two times larger than usually reported since the polar magnetic field is more important in the case of pulsar radiation (Shapiro & Teukolsky 1983). The size of the outer gap for 4U 0142+61 is $f = 0.96$. The distance $d = 2.5$ kpc and solid angle $\Delta\Omega = 1$ are used during the calculation. From Figure 1, the observational upper limits are below the theoretical calculations for large inclination angles (60° , 75°) or when the inner boundary of outer gap can extend to 10 stellar radii (Hirotani et al. 2003; Hirotani & Shibata 2001).

Possible reasons why *Fermi*/LAT has not seen the expected high-energy gamma rays from AXP 4U 0142+61 are as follows.

1. Its radius is smaller than 12 km.
2. Its distance is much larger than 2.5 kpc.

³ Ertan & Cheng (2004) argued that accretion-powered system can also emit high-energy gamma rays if the inner disk rotates faster than the neutron star. However, this criterion cannot be matched for the debris disk around 4U 0142+61 either as a passive disk (Wang et al. 2006) or as a gaseous accretion disk (Ertan et al. 2007).

⁴ <http://www.physics.mcgill.ca/~pulsar/magnetar/main.html>

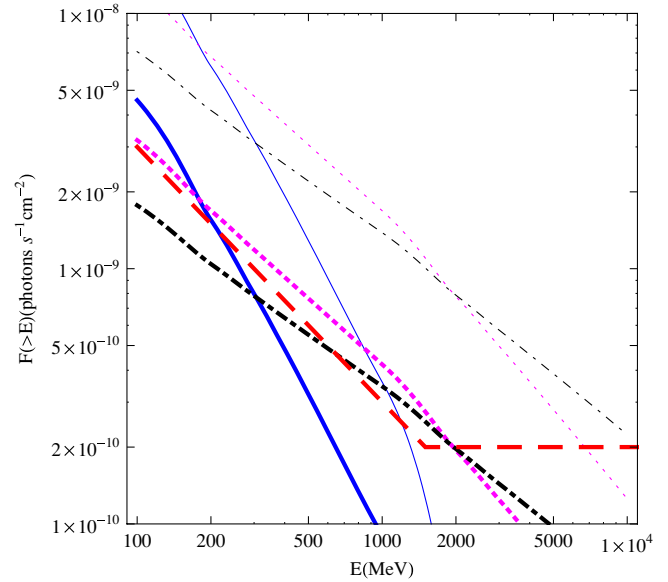


Figure 2. *Fermi*/LAT integral sensitivity curve and model calculations for AXP 4U 0142+61. The solid, dotted, and dot-dashed lines are the same as those in Figure 1, except that the integral flux is shown instead of differential flux. The corresponding thick lines are model calculations when the distance is two times larger, i.e., 5 kpc. The thick dashed line is the *Fermi*/LAT sensitivity curve (Atwood et al. 2009).

(A color version of this figure is available in the online journal.)

3. The inclination angle is small, e.g., 45° .
4. Beaming of gamma-ray radiation.
5. The radiated high-energy gamma-ray photons are absorbed due to internal or external matter.

For order of magnitude estimations, the neutron star radius is often taken as 10 km. However, for realistic equations of state, this choice corresponds to a soft equation of state (Lattimer & Prakash 2007). For a stiff equation of state the radius can be as large as 15 km. A radius of 12 km is a moderate choice (Lattimer & Prakash 2007, their Figure 6). Neutron star equation of state studies (e.g., Tsuruta 2006) also prefer medium to stiff equations of state.

Figure 2 shows the model calculations for AXP 4U 0142+61 when the distance is two times larger, i.e., 5 kpc, along with *Fermi*/LAT sensitivity curve for 5σ detection (Atwood et al. 2009). Even when the distance is two times larger than we presently employed, *Fermi*/LAT should also be able to detect the expected gamma-ray emission of 4U 0142+61. Also in Figure 2, when the inclination angle is small, e.g., 45° , its high-energy radiation is decreased along with an increase in the low energy part (cf. Figure 4 in Cheng & Zhang 2001). Therefore, if the inclination angle is small, although *Fermi*/LAT could not detect 4U 0142+61 in (1–10) GeV band, it could detect 4U 0142+61 in (0.1–1) GeV and lower energy band. In Cheng & Zhang (2001), the inclination angle determines the inner boundary of the outer gap. Recent modeling indicates that the inner boundary may extend to 10 stellar radii (Hirotani et al. 2003; Hirotani & Shibata 2001). Employing this assumption, the corresponding model calculations are shown in Figures 1 and 2.

According to Cheng & Zhang (2001) and references therein, the solid angle for known gamma-ray pulsars ranges from 0.5 to 2.5. Recent *Fermi* observations of gamma-ray pulsars also show a relatively broad pulse profile (Ray & Parkinson 2010). Therefore, the beaming of gamma-ray radiation is not the key factor obscuring our observation of gamma-ray emissions, and

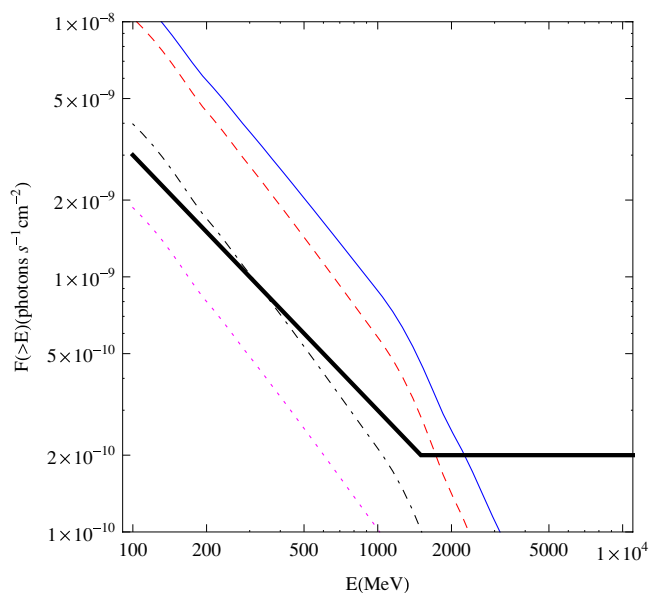


Figure 3. Model calculations for other AXPs and SGRs (Zhang & Cheng 1997; Cheng & Zhang 2001). The inclination angle is chosen as 60° and star radius 10 km. The solid, dashed, dot-dashed, and dotted lines are for AXP 1E 1547.0–5408, AXP 1E 1048.1–5937, AXP XTE J1810–197, and SGR 1806–20, respectively. The thick line is the *Fermi*/LAT sensitivity curve (Atwood et al. 2009).

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this problem can be cleared with future *Fermi*/LAT observations of more AXPs and SGRs.

The magnetic field at the inner boundary of outer gap is 2.6×10^5 G for inclination angle 75° (or 2.6×10^{11} G when the inner boundary is chosen as 10 stellar radii). The absorption of high-energy photons is not significant at the inner boundary due to the weakness of the magnetic field (Ruderman & Sutherland 1975). For AXP 4U 0142+61, it has a debris disk whose photon energy is typically 0.1–1 eV (Wang et al. 2006). The γ - γ absorption is negligible for GeV photons (Zhang & Cheng 1997).

In conclusion, based on the thick outer gap model (Zhang & Cheng 1997), for a variety of the parameter space in the magnetar model, *Fermi*/LAT should be able to detect the expected high-energy gamma-ray emission from AXP 4U 0142+61. This is in conflict with Sasmaz Mus & Gogus (2010).

3. DISCUSSIONS

At the beginning of Section 2, we show that AXPs are not high-energy gamma-ray emitters (f larger than 1) if they are normal neutron stars accreting from fallback disks. Therefore, the non-detection in a *Fermi*/LAT observation of AXP 4U 0142+61 can be naturally explained in the accretion model for AXPs. The spectral energy distribution of 4U 0142+61 indicates an energy break at about 1 MeV (Sasmaz Mus & Gogus 2010). If hard X-ray emission of 4U 0142+61 originates from near the stellar surface, the energy break is also at 1 MeV for a normal neutron star (Zhang & Cheng 1997). Of course the detailed origin of AXP hard X-ray emission needs further studies.

In the accretion model for AXPs (Alpar 2001; Chatterjee et al. 2000; also for SGRs, if they are indeed one population), the long period of AXPs is due to disk braking in the propeller phase. They are now X-ray luminous since they have entered the accretion phase. The bursts of AXPs and SGRs may be due to accretion-induced quakes (AIQs; Xu et al. 2006; Xu 2007),

or quakes and plate tectonics of neutron stars (Rothschild et al. 2002). The AIQ model of Xu et al. (2006) provides a link between persistent emission and bursts. A hybrid model is also possible in which the magnetar field is in higher multipole form and the spin-down is governed by a normal dipole component interacting with a fallback disk (Eksi & Alpar 2003). The recently reported low magnetic field SGR (SGR 0418+5927 with $B_{\text{dipole}} < 7.5 \times 10^{12}$ G; Rea et al. 2010) is consistent with the accretion model.

For AXP 4U 0142+61, as noted in Section 2, it will not emit high-energy gamma rays even if it is a magnetar, when its radius is 10 km instead of 12 km. Therefore, future *Fermi*/LAT observations of more AXPs and SGRs are very necessary. Outer gap predictions in the magnetar domain for other AXPs and SGRs are shown in Figure 3. Model calculations for three AXPs and one SGR are shown, using observational parameters from the McGill AXP/SGR online catalog. For gamma-ray luminous and nearby sources, model calculations of AXP 1E 1547.0–5408 and AXP 1E 1048.1–5937 are well above the *Fermi*/LAT sensitivity curve. Therefore, future *Fermi*/LAT observations of these two sources are highly recommended. Among other AXPs, some are not supposed to be high-energy gamma-ray emitters (f larger than 1), some have relatively low gamma-ray luminosities as shown for AXP XTE J1810–197 in Figure 3, some lies too far away from us. For the two candidate high-energy gamma-ray emitting SGRs, SGR 1806-20 and SGR 1900+14, they are too far away to be detected by *Fermi*/LAT, as shown for SGR 1806–20 in Figure 3.

In conclusion, based on the thick outer gap model (Zhang & Cheng 1997), the non-detection in a *Fermi*/LAT observation of AXP 4U 0142+61 may favor the accretion model. Future *Fermi*/LAT observations of AXP 1E 1547.0–5408 and AXP 1E 1048.1–5937 will help us clarify whether they are magnetars or not.⁵

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⁵ During the submission of this Letter, the *Fermi*-LAT collaboration have published their observations for all known AXPs and SGRs (Abdo et al. 2010), where still no significant detection is reported. This result is in favor of our conclusions.

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