SEARCH FOR HIGH-ENERGY GAMMA-RAY EMISSION FROM AN ANOMALOUS X-RAY PULSAR, 4U 0142+61

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ABSTRACT

Until 2004, anomalous X-ray pulsars (AXPs) were known as strong emitters of soft X-rays only (< 10 keV). The discovery of hard X-ray component from AXPs provided important insight about their emission properties while it posed a serious challenge to explain its origin. The physical mechanism of the hard emission component has still not been fully resolved. We investigate the high-energy gamma-ray properties of the brightest AXP, 4U 0142+61 using data collected with the Large Area Telescope on board Fermi Gamma-ray Space Telescope to establish the spectral behavior of the source on a very broad energy span and search for pulsed emission. Here, we present our results of detailed search for the persistent and pulsed high-energy gamma-ray emission from 4U 0142+61 which result in no significant detection. However, we obtain upper limits to the persistent high-energy gamma-ray emission flux which helps us to constrain existing physical models.

Subject headings: pulsars: individual (AXP 4U 0142+61) – gamma-rays: stars

1. INTRODUCTION

Anomalous X-ray pulsars (AXPs) have been intriguing sources since their discovery in early 1980s (Fahlman & Gregory 1981). They are bright X-ray sources with X-ray luminosities (below 10 keV) in the range of $10^{33}-10^{36}$ erg s$^{-1}$. They spin rather slowly and their spin periods clustered in a narrow range of 2-12 s. The lack of any evidence for binary nature (e.g., Doppler modulation in their long term pulse periods) eliminates the possibility that they are accreting matter from a donor. Their spin down rates are relatively large, ranging between $10^{-10}$ and $10^{-12}$ s$^{-1}$. Their rotational energy loss is insufficient by orders of magnitudes to provide the observed X-ray luminosities. AXPs are commonly regarded as young isolated neutron stars that are powered by their extremely strong magnetic fields, $B \gtrsim 10^{14}$ G (Duncan & Thompson 1992). Such strong magnetic fields can efficiently slow these young systems down via magnetic breaking and provide energy for the emitted X-rays via diffusion of evolving magnetic field (Thompson & Duncan 1996). A detailed review on AXPs can be found in Mereghetti (2008) and Woods & Thompson (2004).

A major observational development in AXPs was the discovery of hard X-ray emission from AXPs 1E 1841-045 (Kuiper et al. 2004), 4U 0142+61 (den Hartog et al. 2004) and 1RXS J170849.0-400910 (Revnivtsev et al. 2004). 1E 1841-045, located at the center of supernova remnant (SNR) Kes 73, is the first AXP from which non-thermal pulsed hard X-ray/soft gamma-ray emission was discovered (Kuiper et al. 2004). The pulsed nature of this emission eliminates the possibility of its SNR origin. Spectral studies of this source using INTEGRAL observations in the 20–300 keV band revealed a power–law shape with an index of 1.39 ± 0.05 but no evidence of spectral break (Kuiper et al. 2006). The hard X-ray emission from 1RXS J170849.0-400910 was discovered in the Galactic Plane Survey observations with INTEGRAL (Revnivtsev et al. 2004) and shown to be pulsed as well (Kuiper et al. 2006, den Hartog et al. 2008). Finally, hard emission component from 4U 0142+61 was discovered during INTEGRAL observations of the Cassiopeia region (den Hartog et al. 2004). Detailed studies with 2.37 Ms INTEGRAL observations showed a power law spectrum up to about 230 keV with an index of 0.93 ± 0.06 (den Hartog et al. 2008). Based on the logparabolic function fit to the INTEGRAL SPI and ISGRI observations, they estimate a peak energy of the spectral energy distribution to be $\sim 228$ keV (den Hartog et al. 2008), and $20–150$ keV flux as $(8.97 \pm 0.86) \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. It is important to note that the energy emitted above 15 keV is comparable or larger than that in the soft X-ray band (that is, below 10 keV, see e.g., den Hartog et al. 2008).

The physical nature of the hard X-ray / soft gamma-ray emission is still not well understood. Beloborodov & Thompson (2007) proposed that the hard X-ray emission could originate from a plasma corona around the magnetar. They suggest that such a corona around magnetars can be formed via starquakes that could shear the neutron star crust and its external magnetic field. Heil & Hernquist (2005a,b) proposed the fast-mode break down model in which an optically thick fireball produced by the magnetohydrodynamics waves created near the surface of the neutron star. Further they suggest that if fast modes are not strong enough to yield an optically thick fireball, the produced non-thermal emission would be sufficient to explain the observed high-energy emission from soft gamma repeaters and AXPs. Another attempt to explain the hard X-ray emission is by Baring & Harding (2007). They suggest that the upscattered surface thermal X-ray photons as the source of observed non-thermal hard X-ray emission from AXPs.

In order to understand the nature of the hard emission component of AXPs, it is crucial to establish their

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spectral shapes on a wide range in the energy domain. In particular, it is important to determine where their spectral energy distribution peak. Thanks to the Large Area Telescope (LAT) on board Fermi Gamma-ray Space Telescope (Fermi), we are now able to investigate high-energy behavior of these sources with an unprecedented data quality.

In this paper, we performed detailed search for persistent and pulsed high-energy gamma-ray emission from 4U 0142+61 using Fermi/LAT observations. We also employed contemporaneous Rossi X-ray Timing Explorer (RXTE) observations to obtain the spin ephemeris of the source. In Section 2, we describe the observations used and details of data analysis. We present our results in Section 3 and discuss their implications in Section 4.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. Fermi/LAT

LAT is one of the two instruments on board Fermi operating in the energy band of 20 MeV−300 GeV. It is a pair conversion telescope with a high-resolution silicon tracker, calorimeter, anticoincidence detector, programmable trigger and data acquisition system (Atwood et al. 2009). Since 2008 August 4, the LAT has been operating as an all sky monitor in high-energy gamma-rays, covering the full sky in approximately every 3 hr.

We accumulated the LAT data within a 15° radius centered at 4U 0142+61, collected from 2008 August 4 to 2010 April 29 with an exposure time of ~31.7 Ms. We also performed spectral analysis using a 2° region around the source in order to completely avoid contamination from the nearby bright sources. We performed our unbinned likelihood analysis using ScienceTools v9r15p2 with P6_V3_DIFFUSE set as the instrumental response. In the event selection process, we set the maximum zenith angle to 105° in order to eliminate background gamma-rays due to the Earth limb. All time intervals where the zenith cut intersects the region were excluded. In Figure 2.1, we present the count map image of the 40° region around 4U 0142+61. The diffuse gamma-ray emission from the Milky Way was modeled with the latest model, gll_iem_v02.fit. We also used isotropic_jem_v02.txt to account for the extragalactic isotropic diffuse emission and residual instrumental background. The spectral fits and flux calculations were done with the python version of gtlike, pyLikelihood.

For timing analysis, photon arrival times of all events within the 2° extraction region around 4U 0142+61 were converted to that at the solar system barycenter using gtmdbary of ScienceTools.

2.2. RXTE

To search for pulsed high-energy gamma-ray emission from 4U 0142+61, we obtained the precise spin ephemeris of the source using contemporaneous RXTE observations. On board RXTE, there are three scientific payloads: the Proportional Counter Array (PCA) that is sensitive to photon energies between 2−60 keV, the High Energy X-ray Timing Experiment, sensitive to photons in the 15−250 keV photons and the All Sky Monitor. We have employed only the PCA observations to achieve our goal.

4U 0142+61 has been monitored with the RXTE periodically for the last ~8 years with pointings almost uniformly spaced, usually by about two weeks. We have selected 53 RXTE observations that were performed between 2008 August 4 and 2010 April 30 (under the Program IDs: P93019, P94019 and P05019) which covers the investigated LAT observing span. Individual RXTE pointings are typically between 3 and 4 ks long and the total exposure time of all selected observations is about 196 ks. For each observation, we extracted events in the 2−10 keV range collected with the PCA and converted their arrival times to the solar system barycenter using the fxabay tool of HEASoft 6.8.

3. RESULTS

3.1. Search for Persistent Emission

As evident from Figure 2.1, 4U 0142+61 is clearly not detected in the LAT energy passband. A point source search using the filtered event list with the gtfindsrc tool of ScienceTools results in a potential source whose coordinates are inconsistent with that of 4U 0142+61, therefore yields no detection.

In order to obtain very-high-energy gamma-ray flux upper limits of 4U 0142+61, we fitted the data from the 15° region radius. We added all bright cataloged sources and recently discovered blazar (Verdenbroecke et al. 2010) within this region of interest into the model as well as the galactic diffuse and extragalactic diffuse emission leaving their model parameters free. The fit yields a test statistics (TS) value of ~0.23 which implies a detection significance less than 1σ. The 3σ flux upper limits with a power law index 2.5 are 2.32 × 10^{-6} MeV cm^{-2} s^{-1} in the 0.1-2 GeV band and 1.28 × 10^{-6} MeV cm^{-2} s^{-1} in the 1.0-10.0 GeV band. Note here that the spectral parameters and fluxes of the cataloged sources obtained in the latter fit are consistent with the catalog values, showing that our analysis is robust.

We performed similar spectral modelling for the data of the 2° region with a power law model of index 3 as well as the galactic diffuse and extragalactic isotropic diffuse emission models. The resulting TS value is ~3 which implies a detection significance less than 2σ. We chose the 0.2-1.0 and 1.0-10.0 GeV energy bands for flux calculations and find 3σ upper limits to the source flux in these energy bands as 5.72 × 10^{-6} MeV cm^{-2} s^{-1} and 1.29 × 10^{-6} MeV cm^{-2} s^{-1}, respectively. In Figure 3, we present the high-energy gamma-ray flux upper limits of 4U 0142+61 in the νF_ν representation along with its low energy gamma-ray behavior (den Hartog et al. 2008, the data obtained from). We discuss their implications in §4.

3.2. Search for Pulsed Emission

We employed a Fourier based epoch folding technique to obtain the spin ephemeris of 4U 0142+61 using RXTE/PCA observations covering the time span of the LAT exposure of the source. We first generated the
The pulse profile of the source using three consecutive PCA observations around the epoch (MJD 54713.5). Then, we grouped observations in order for them to be spaced at least 0.2 days apart from each other, and we cross correlated the pulse profile of each group of pointings with the template profile to determine the phase shift of each pointing with respect to the template. Finally, we fit the phase shifts with a polynomial to obtain the spin ephemeris. In Figure 3.2, we present the phase shift and the best fitting model, that is a third-order polynomial (\(\chi^2/\text{degrees of freedom} = 59.6/42\)). We tabulate the best fit spin ephemeris parameters of 4U 0142+61 in Table 1.

### TABLE 1
**Spin ephemeris of 4U 0142+61**

| Parameter          | Value                 |
|--------------------|-----------------------|
| Range (MJD)        | 54682.6 – 55315.1     |
| Epoch (MJD)        | 54713.5               |
| \(\nu\) (Hz)       | 0.1150900026(9)       |
| \(\dot{\nu}\) (10^{-14} Hz s^{-1}) | -2.745(8) |
| \(\ddot{\nu}\) (10^{-23} Hz s^{-2}) | 3.6(3) |

To search for pulsed high-energy gamma-ray emission from 4U 0142+61, we generated the LAT pulse profiles of the source in the 0.2-1.0 GeV and 1.0-10.0 GeV energy ranges using the precise PCA spin ephemeris obtained. We find that both LAT profiles are consistent with random fluctuations with respect to its mean. We calculate a 3\(\sigma\) upper limit to the rms pulsed fraction of 1.5% in the 0.2-1.0 GeV band and 2.3% in the 1.0-10.0 GeV band. We also investigated the lower energy part of the LAT passband (30-200 MeV), which also resulted with no evidence of pulsed emission; the 3\(\sigma\) rms pulsed fraction upper limit is 1.6%.

### 4. DISCUSSION

We searched for both persistent and pulsed high-energy emission from the AXP 4U 0142+61 using Fermi/LAT data. We find no significant detection in either of the two objectives. Nevertheless, we obtained 3\(\sigma\) upper limits for the high energy persistent emission in the 0.2-1.0 GeV and 1.0-10.0 GeV ranges of \(5.72 \times 10^{-6}\) MeV cm^{-2} s^{-1} and \(1.29 \times 10^{-6}\) MeV cm^{-2} s^{-1}, respectively. As for the pulsed emission, a 3\(\sigma\) upper limit to the RMS pulsed amplitude in the 0.2-1.0 GeV range is 1.5% and in the 1.0-10.0 GeV range is 2.3%. The search in the lower energy LAT passband (30-200 MeV) also did not yield a pulsed emission. The 3\(\sigma\) rms pulsed amplitude upper limit is 1.6%. Our LAT upper limits are much lower than high pulsed fraction (up to 100%) seen in hard X-rays with INTEGRAL (den Hartog et al. 2008).

In order to establish the spectral shape of 4U 0142+61 on a wide energy range, we constructed the \(\nu F_\nu\) spectrum of the source in the 15 keV–10 GeV range by adopting the hard X-ray spectrum presented in den Hartog et al. (2008) and placing the upper limits calculated in this work. den Hartog et al. (2008) fitted the INTEGRAL/ISGRI data with a simple power law model of index 0.93 ± 0.06. We present this fit with dashed lines in Figure 4. We place an upper limit curve, which is the line connecting the two LAT upper limit measurements (as shown with solid line in Figure 4), is also a power law with an index of −0.76. These two curves intersect with each other at \(\sim 1.1\) MeV which is an upper limit to the spectral break energy. Note that the spectral break upper limit is consistent with den Hartog et al. (2008) measurement of...
279$^{+65}_{-41}$ keV obtained by fitting a logparabolic function to the combined XMM-Newton, INTEGRAL/ISGRI, INTEGRAL/SPI and CGRO/COMPTEL data.

Our estimated upper limit to the spectral break energy is in accordance with the coronal emission model by Beloborodov & Thompson (2007). According to their model, photons with energies in excess of $\gtrsim 1$ MeV would be trapped in the ultrastong magnetic fields ($B \gtrsim 10^{14}$ G). In such a case photons would either split into two photons or they would create an electron-positron pair, therefore, suppressing the emission from the inner corona above $\sim 1$ MeV. Our estimate of the spectral break energy upper limit also agrees with the predictions of the quantum electrodynamics model by Heyl & Hernquist (2005a,b) as they expect the lower limit to the break energy to be around 1 MeV. On the other hand, they claim that if a source has a significant excess emission in optical wavelengths, as in the case of 4U 0142+61 (Hulleman et al. 2000), its $\nu F_\nu$ spectrum should continuously increase in the 10-200 MeV range. Note that optical emission originates from the neutron star itself (Kern & Martin 2002, Dhillion et al. 2005) and from a disk around 4U 0142+61 (Wang et al. 2006, Ertan & Caliskan 2006). However, the origin of the excess optical emission in 4U 0142+61 is not clear. If the excess optical emission originates from the compact object, our results place constraint, although not stringent, on the quantum electrodynamics model due to the lack of increase in the 10-200 MeV range in the $\nu F_\nu$ spectrum. On the other hand, if the disk provides a significant contribution to the observed emission, then the optical radiation from the neutron star itself would not be excessive and the quantum electrodynamics model would still remain feasible.

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Fig. 3.— Wide band $\nu F_\nu$ spectrum of 4U 0142+61: INTEGRAL/ISGRI (20-300 keV) in black (stars), INTEGRAL/SPI (20-1000 keV) in red (open squares) and CGRO/COMPTEL (0.75-30 MeV) $2\sigma$ upper limits in black (data constructed from den Hartog et al. [2008]). Fermi/LAT upper limits (in the 0.2-1.0 GeV and 1.0-10.0 GeV) obtained using the $2^\circ$ extraction region are shown in blue diamonds and that of $15^\circ$ extraction region in red triangles. Dashed line is the best fit power law model to the ISGRI data points (den Hartog et al. [2008]). Solid line shows the power law upper limit trend of the $2^\circ$ Fermi/LAT region.

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