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Hard X-ray emission cutoff in the anomalous X-ray pulsar 4U 0142+61 detected by *INTEGRAL* [*]

Wei Wang[1], Hao Tong[2] and Yan-Jun Guo[3]

[1] National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China; *wangwei@bao.ac.cn*
[2] Xinjiang Astronomical Observatory, Chinese Academy of Sciences, Urumqi 830011, China
[3] School of Physics, Peking University, Beijing 100871 , China

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Abstract The anomalous X-ray pulsar 4U 0142+61 has been studied with observations from *INTEGRAL*. The hard X-ray spectrum in the range 18–500 keV for 4U 0142+61 was derived using nearly nine years of *INTEGRAL*/IBIS data. We obtained the average hard X-ray spectrum of 4U 0142+61 with all available data. The spectrum of 4U 0142+61 can be fitted with a power law that includes an exponential high energy cutoff. This average spectrum is well fitted by a power law with $\Gamma \sim 0.51 \pm 0.11$ plus a cutoff energy at $128.6 \pm 17.2\,$keV. The hard X-ray flux of the source from 20–150 keV showed no significant variations (within 20%) from 2003–2011. The spectral profiles have some variability over the nine years such that the photon index varies from 0.3–1.5 and the cutoff energies from 110–250 keV. The detection of the high energy cutoff around 130 keV shows some constraints on the radiation mechanisms of magnetars and possibly probes the differences between magnetar and accretion models for this special class of neutron stars. Future *HXMT* observations could provide stronger constraints on the hard X-ray spectral properties of this source and other magnetar candidates.

Key words: pulsars: individual (4U 0142+61) — stars: magnetar — stars: neutron

1 INTRODUCTION

Anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs) are a special class of neutron stars. They generally have the following observed features (Mereghetti 2008): spin period in the range 2–12 s; young characteristic age (10–100 kyr); some AXPs are associated with supernova remnants; an inferred dipole magnetic field[1] of $10^{14} - 10^{15}\,$G; persistent X-ray luminosity (0.1–10 keV) in the range $10^{34} - 10^{36}\,\mathrm{erg\,s^{-1}}$ which is higher than their spin-down power; in the soft X-ray band, they have very soft spectra, with $kT \sim 0.5\,$keV or photon index $\Gamma \sim 2 - 4$; recurrent bursts (including giant flares); the absence of massive companion stars. At present, growing evidence indicates that AXPs and SGRs may be isolated neutron stars with an ultrastrong magnetic field (with

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[1] A low magnetic field magnetar should be treated separately (Rea et al. 2010; Tong & Xu 2012).

a magnetic field higher than the quantum critical point $B_{\rm QED} = m_e^2c^3/e\hbar = 4.4 \times 10^{13}$ G), which are so called magnetars (Thompson & Duncan 1996).

Non-thermal hard X-ray emissions above 15 keV in AXPs were discovered by some missions like *INTEGRAL*, *RXTE* and *Swift* (Kuiper et al. 2004, 2006; Wang 2008). The hard X-ray properties of AXPs are quite different from their spectral properties in soft X-ray bands below 10 keV. In soft X-ray bands, the spectra of AXPs are generally attributed to a thermal component with a temperature of $kT \sim 0.35-0.6$ keV, and a soft power law component with $\Gamma \sim 2-4$ (Enoto et al. 2010a). However, in hard X-ray bands above 20 keV, AXPs show a non-thermal emission component with a photon index of $\Gamma \sim 0.5 - 1.5$, and the pulse fraction is larger than 50% or even near 100% (Kuiper et al. 2004, 2006). The luminosity in hard X-ray emission, which is similar to that in soft X-ray bands, is also much higher than the spin-down power of AXPs. Thus the hard X-ray emission component should come from other sources of energy, like magnetar activity. The physical mechanism that produces this non-thermal hard X-ray emission is still unknown. In addition, the new discovery of the hard X-ray spectrum above 10 keV showed no cut-off up to 100 keV, implying that the luminosity above 10 keV could possibly be the dominant component in the softer band, which provides a new challenge to the magnetar model.

The discovery of the spectral cut-off in hard X-rays is thus very important for constraining the total energy released from AXPs, and furthermore provides strong constraints on the magnetar model. Kuiper et al. (2006) use archived CGRO/COMPTEL data to constrain the spectrum of four AXPs in MeV bands, suggesting that the hard X-ray emission could not extend to MeV ranges (maybe showing a cutoff below 1 MeV). Wang (2008) obtains the hard X-ray spectra of AXPs with the 2-year *Swift* data from 15–200 keV, suggesting possible cutoff energies around 100–150 keV for hard X-ray emissions from 1E 1841–045 and 4U 0142+61. Up to now, the spectral cutoff properties of AXPs in hard X-rays are not well understood.

In this work, we will study 4U 0142+61, the brightest of all AXPs in X-ray bands with *INTEGRAL*/IBIS. The soft X-ray spectrum of 4U 0142+61 from 0.5–10 keV by *XMM-Newton* is described well by a blackbody with temperature 0.41 keV plus a powerlaw with photon index 3.88 and $N_{\rm H} \sim 1.0 \times 10^{22}\ {\rm cm}^{-2}$ (Rea et al. 2007). According to the extinction of its optical counterpart, Hulleman et al. (2000) estimated that the pulsar must be at a distance > 2.7 kpc. Above 20 keV, 4U 0142+61 shows a non-thermal spectrum with a photon index of $\sim 0.9 - 1$ with *RXTE* and *Swift* data (Kuiper et al. 2006; Wang 2008). den Hartog et al. (2008) used all available observations of 4U 0142+61 by *INTEGRAL*, *RXTE*, *XMM-Newton* and *ASCA* to analyze X-ray spectral properties, and found a mean photon index of ~ 0.9 from 20–150 keV. Suzaku also observed 4U 0142+61 up to 70 keV (Enoto et al. 2011), and suggested that the hard X-ray component can be fitted by a power law with $\Gamma \sim 0.9$, and a possible cutoff energy > 150 keV. *INTEGRAL*/IBIS is a highly sensitive hard X-ray imager from 18–500 keV. Observations with IBIS are now available from 2003 to 2011. Exposures of deeper observations of the source 4U 0142+61 will help to constrain the spectral shape of a typical AXP in hard X-ray to soft gamma-ray bands.

We first introduce the *INTEGRAL* observations of the source and data analysis in Section 2. In Section 3, the hard X-ray spectral properties of the AXP 4U 0142+61 are presented, and we concentrate on the spectral cutoff feature. The spectral variations of 4U 0142+61 from 2003–2011 from 18–500 keV are shown in Section 4. Finally the physical implications of this spectral cutoff are discussed in Section 5. A brief conclusion is given in Section 6.

2 *INTEGRAL* OBSERVATIONS

4U 0142+61 was observed with frequent pointing observational surveys of Cassiopeia from 2003–2011 by the *INTEGRAL* satellite. We mainly use the observational data obtained by the INTEGRAL Soft Gamma-Ray Imager (IBIS-ISGRI, Lebrun et al. 2003) which has a $12'$ (FWHM) angular resolution and arcmin source location accuracy in the energy band 18–500 keV.

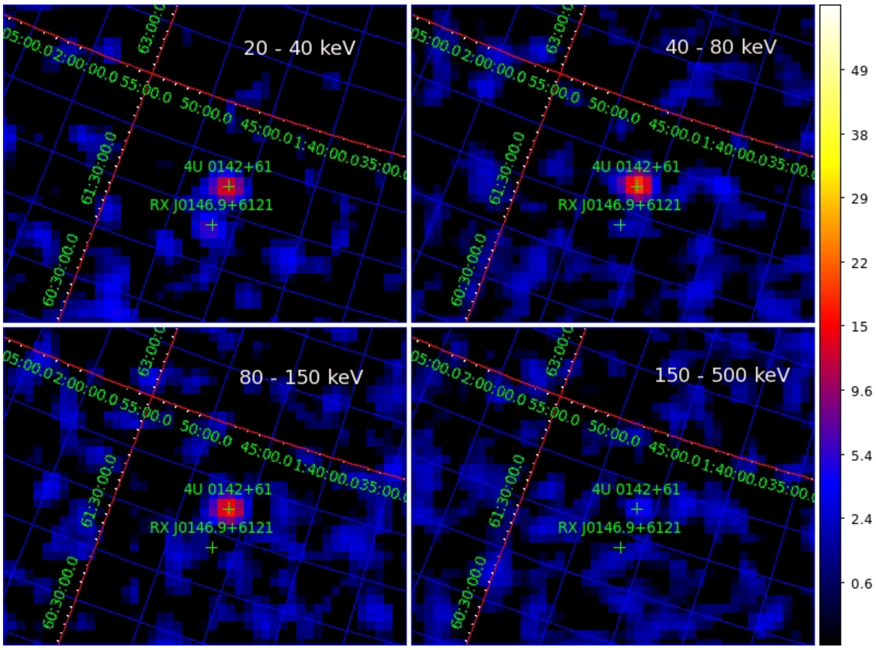

Fig. 1 Mosaicked maps around AXP 4U 0142+61 in equatorial J2000 coordinates as seen with *INTEGRAL*/IBIS that show significance of detection in four energy bands: 20–40 keV, detection significance level is $15.6\,\sigma$; 40–80 keV, $20.9\,\sigma$; 80–150 keV, $17.8\,\sigma$; 150–500 keV, $< 5\,\sigma$.

We use the available archival data from the INTEGRAL Science Data Center (ISDC) where 4U 0142+61 was within $\sim 12^\circ$ of the pointing direction of *INTEGRAL*/IBIS observations from 2003–2011. The total corrected on-source time obtained in our analysis is about 3.8 Ms after excluding the bad data due to solar flares and the *INTEGRAL* orbital phase near the radiation belt of the Earth. The analysis was done with the standard *INTEGRAL* off-line scientific analysis (OSA, Goldwurm et al. 2003) software, ver. 10. Individual pointings for all collected IBIS data processed with OSA 10 were mosaicked to create sky images for the source detection in the given energy ranges.

In Figure 1, sky images in four energy bands around 4U 0142+61 are displayed. In the energy range 20–40 keV, 4U 0142+61 is detected with a significance level of $15.6\,\sigma$, and a nearby source RX J0148.9+6121 is a high mass X-ray binary. In the range 40–80 keV, the source RX J0148.9+6121 cannot be detected by IBIS, but 4U 0142+61 is detected with a significance level of $20.9\,\sigma$. In the range 80–150 keV, 4U 0142+61 is still detected with a high significance level of $17.8\,\sigma$. However, above 150 keV, the AXP cannot be detected by IBIS. Non-detection of 4U 0142+61 above 150 keV suggests the existence of a possible high energy cutoff.

3 AVERAGE HARD X-RAY SPECTRUM OF 4U 0142+61

After forming the mosaicked images in the different energy ranges, we can then extract the average hard X-ray spectrum from 18–500 keV by IBIS. The spectrum of 4U 0142+61 in the form of $E^2 \times F$ obtained by IBIS is presented in Figure 2. The spectral analysis software package used here is XSPEC 12.6.0q. In the spectral fittings, we have tried three simple spectral models to constrain the hard X-ray spectral properties of the AXP.

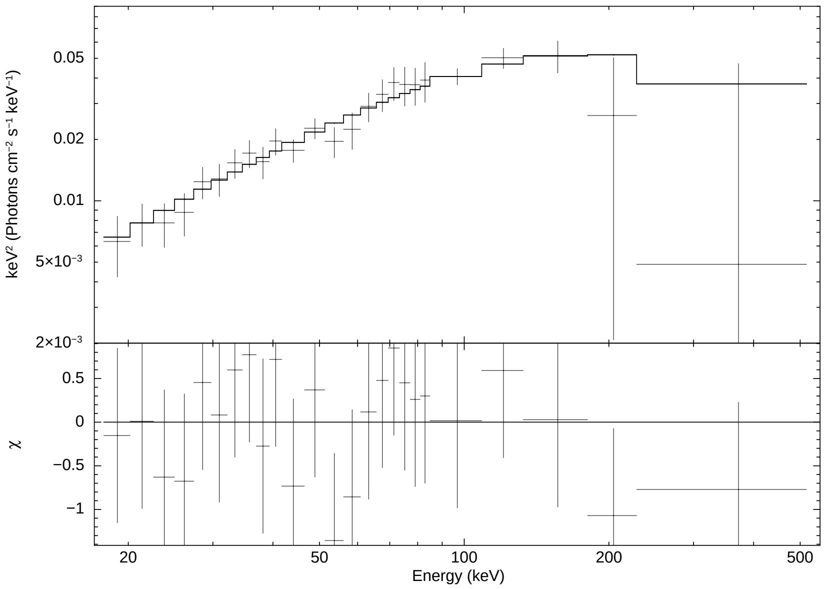

Fig. 2 The hard X-ray spectrum of 4U 0142+61 from 18–500 keV obtained by *INTEGRAL*/IBIS. The spectrum is fitted well by a power law plus an exponential cutoff model, with a photon index of ~ 0.5 and high energy cutoff of ~ 130 keV.

Table 1 The Hard X-ray Spectral Properties of AXP 4U 0142+61 in the range 18–500 keV

Model	Γ/kT (keV)	Cutoff Energy (keV)	Flux	Reduced χ^2 (d.o.f.)
Power law	1.09 ± 0.07		1.39 ± 0.11	1.485 (24)
Bremsstrahlung	179±58		0.87 ± 0.12	4.031 (24)
Cutoff power law	0.51 ± 0.11	128.6 ± 17.2	1.27 ± 0.12	0.614 (23)

Three different spectral models are applied to fit the spectrum: a single power law model, a thermal bremsstrahlung model and a power law plus an exponential cutoff model. The flux is given in units of 10^{-10} erg cm^{-2} s^{-1} in the range 18–200 keV. The error bars represent 1σ.

In Table 1, we also show the spectral parameters fitted with the three models: a single power law model, a thermal bremsstrahlung model and a power law plus an exponential cutoff model. The bremsstrahlung model gives a temperature of $\sim$ 200 keV, however it cannot give a good fit to the spectrum (the reduced χ^2 is higher than 4). The single power law model yields a photon index of ~ 1, but the fitting is not very satisfying. The data points representing spectra in the bands 18–35 keV and above 150 keV cannot be fitted well. The spectrum is then fitted with a cutoff power law model, giving a photon index of ~ 0.5 and a spectral cutoff around $\sim 129 \pm 17$ keV. The best fitted spectral model is also shown in Figure 2.

Thus a simple spectral analysis with different models supports the fact that the hard X-ray emissions from the brightest AXP 4U 0142+61 should have a spectral cutoff around 130 keV. The hard X-ray emission cannot extend to the higher energy range above 300 keV for AXPs. From 18–200 keV, the derived X-ray flux of 4U 0142+61 is about $(1.27 \pm 0.12) \times 10^{-10}$ erg cm^{-2} s^{-1}. This flux is lower than that given by den Hartog et al. (2008) which reported a hard X-ray flux of $(1.50 \pm 0.08) \times 10^{-10}$ erg cm^{-2} s^{-1} from 20–229 keV with a simple power law fitting. In Table 1, the power law model generated a hard X-ray flux of $(1.39 \pm 0.11) \times 10^{-10}$ erg cm^{-2} s^{-1} which is still consistent with the results by den Hartog et al. (2008). Assuming a distance of 3 kpc, the obtained total hard X-ray luminosity is $\sim 1.5 \times 10^{35}$ erg s^{-1}. This luminosity is still similar to the total X-ray luminosity in softer bands (like 0.5–10 keV, see Rea et al. 2007).

4 SPECTRAL VARIATIONS IN HARD X-RAY FOR 4U 0142+61

In Section 3, we derived the average spectrum of 4U 0142+61 with all available data from *INTEGRAL*. This source or properties of its spectrum can vary in different time intervals (also see den Hartog et al. 2008).

In Figure 3, we present variations in the IBIS count rate with years in two energy bands: 20–60 keV and 60–150 keV. From 2003–2011, the total IBIS count rate of 4U 0142+61 from 20–150 keV remains relatively stable around $\sim 0.7 - 0.9$ cts s^{-1}; the variations are less than 20%. Our result confirms that 4U 0142+61 is a stable, persistent hard X-ray emission source, which was determined by previous *INTEGRAL* studies (Kuiper et al. 2006; den Hartog et al. 2008). However, the count ratio of two energy bands (60–150 keV to 20–60 keV) changes with time, in the range 0.3–0.9, suggesting that the spectral properties of 4U 0142+61 should vary with different time intervals.

To show details of the spectral features of 4U 0142+61 over time from 2003–2011, we derived the spectra in the range 18–500 keV in different time intervals as noted in Figure 3. In 2010, two observations implied there was a similar hardness ratio (60–150 keV to 20–60 keV) in 4U 0142+61, so we combined two observations to extract the hard X-ray spectrum for a higher significance level. Finally, we extracted the spectra of 4U 0142+61 from 18–500 keV in eight time intervals (see Table 2). These spectra shown in Figure 4 are all fitted with a simple power law model for comparison.

In Table 2, we display the spectral parameters of fitting eight spectra with both a power law model and a cutoff power law model. From Table 2, we can clearly see variations in the spectral properties of the source over time. In the results from the simple power law fitting, we find the photon index varies from 0.7–1.6, but the total flux from 20–150 keV (around 8×10^{-11} erg cm^{-2} s^{-1}) did not significantly change from 2003–2011. If the cutoff power law model was applied to the spectral fittings, the derived cutoff energies also changed with time, from ~ 110 keV to higher than 250 keV.

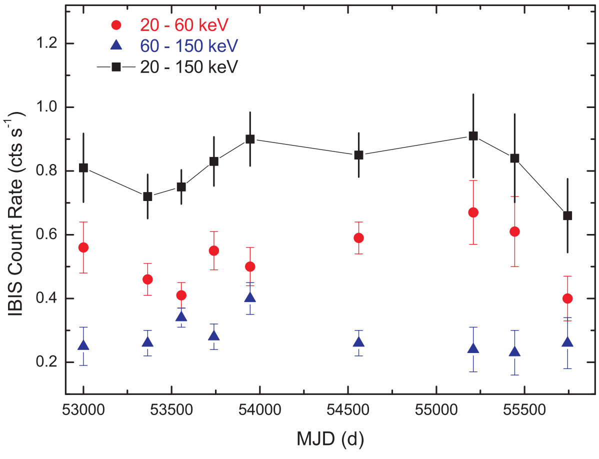

Fig. 3 Variations of the background subtracted IBIS count rate for 4U 0142+61 in the energy bands: 20–60, 60–150 and 20–150 keV from 2003–2011. The error bars express a confidence level of 1σ.

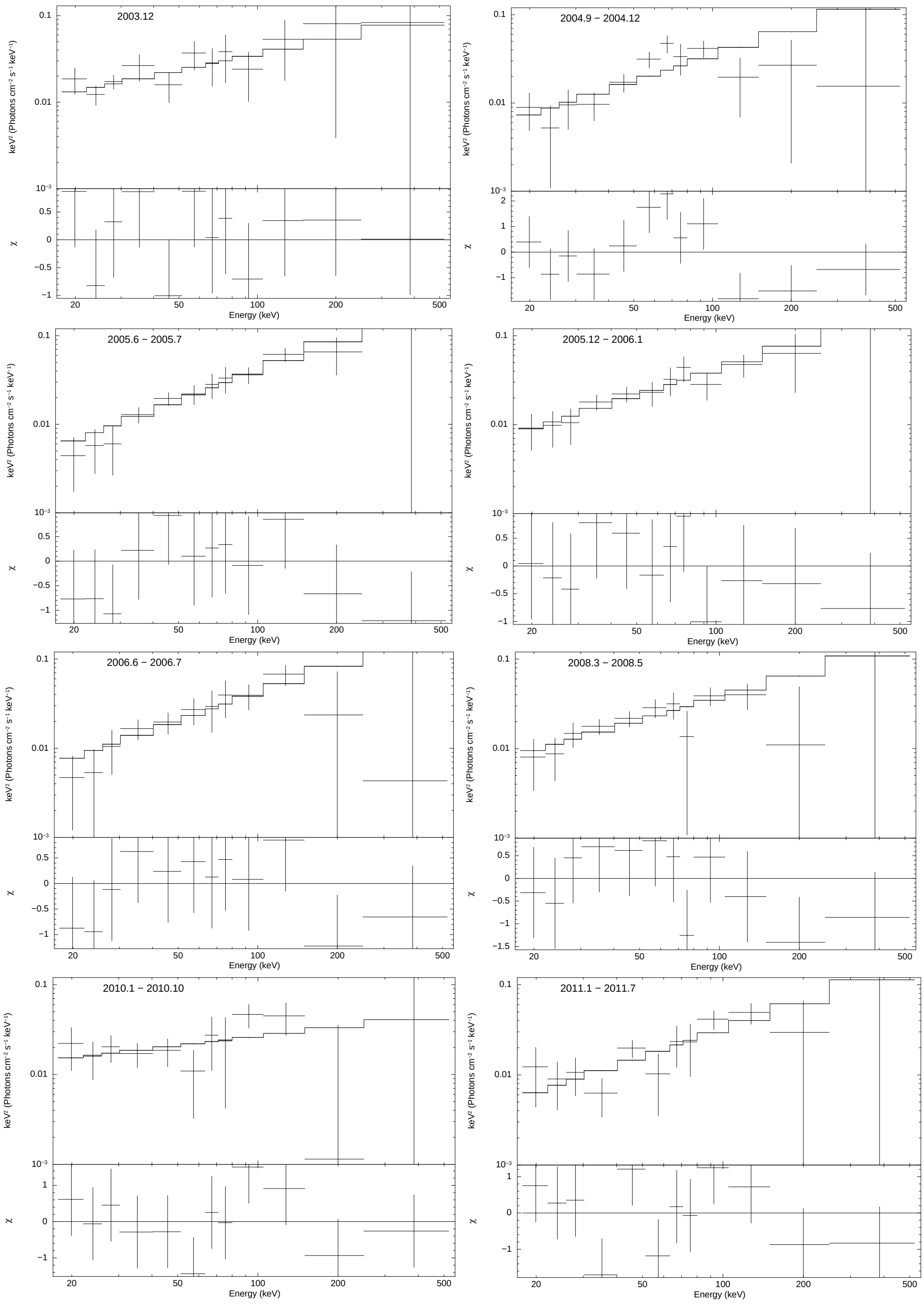

Fig. 4 The hard X-ray spectra of 4U 0142+61 from 18–500 keV obtained by *INTEGRAL*/IBIS in eight different time intervals. The spectra are all fitted with a simple power law model whose parameters are presented in Table 2.

Table 2 Spectral Variations in Hard X-ray for AXP 4U 0142+61 in the Range 18–500 keV for Eight Time Intervals

Time	Model	Γ	Cutoff Energy (keV)	Flux	Reduced χ^2 (d.o.f.)
2003.12	Power law	1.37 ± 0.21		8.6 ± 1.1	1.023 (11)
	Cutoff power law	1.34 ± 0.62	265.5 ± 120.9	8.5 ± 1.2	0.896 (10)
2004.9–2004.12	Power law	1.00 ± 0.16		7.3 ± 1.1	1.498 (11)
	Cutoff power law	0.70 ± 0.45	161.2 ± 29.9	7.4 ± 1.1	1.116 (10)
2005.6–2005.7	Power law	0.85 ± 0.12		8.2 ± 1.0	0.968 (11)
	Cutoff power law	0.71 ± 0.31	258.5 ± 100.4	8.3 ± 1.0	0.562 (10)
2005.12–2006.1	Power law	1.07 ± 0.14		8.7 ± 0.9	0.794 (11)
	Cutoff power law	0.92 ± 0.42	260.4 ± 108.6	8.8 ± 1.0	0.365 (10)
2006.6–2006.7	Power law	0.95 ± 0.17		8.6 ± 0.8	1.282 (11)
	Cutoff power law	0.29 ± 0.32	112.9 ± 39.7	8.7 ± 0.9	0.531 (10)
2008.3–2008.5	Power law	1.29 ± 0.17		8.1 ± 0.9	0.986 (11)
	Cutoff power law	1.01 ± 0.50	191.14 ± 49.6	8.2 ± 1.0	0.835 (10)
2010.1–2010.10	Power law	1.56 ± 0.23		7.2 ± 1.0	0.907 (11)
	Cutoff power law	1.50 ± 0.61	168.8 ± 47.9 keV	7.2 ± 1.1	0.868 (10)
2011.1–2011.7	Power law	1.00 ± 0.22		6.9 ± 1.3	1.201 (11)
	Cutoff power law	0.99 ± 0.56	195.1 ± 55.8 keV	6.9 ± 1.3	1.230 (10)

Two different spectral models are applied to fit the spectrum: a single power law model and a power law plus an exponential cutoff model. The flux is given in units of 10^{-11} erg cm^{-2} s^{-1} in the range 20–150 keV.

5 IMPLICATIONS OF A HARD X-RAY CUTOFF

Hard X-ray tails have been detected in several AXPs (e.g, 4U 0142+61, 1E 1841–0451, 1RXS J1708–40, see Kuiper et al. 2006; Wang 2008), and also detected in magnetar/SGR activities (SGR 1900+14, SGR 1806–20, SGR 0501+4516 and 1E 1547.0–5408; see Esposito et al. 2007; Rea et al. 2009; Enoto et al. 2010b). During and after magnetar activities, the hard X-ray tails also show hard spectra with a photon index of $\sim 0.8 - 1.5$ (Rea et al. 2009; Enoto et al. 2010a,b; Kuiper et al. 2012). In particular, the hard X-ray spectrum of the magnetar 1E 1547.0–5408 showed a hint of a high energy cutoff around 100 keV during its activity in 2009 (Enoto et al. 2010b). These hard X-ray properties during magnetar activities are still similar to those of the persistent emission in 4U 0142+61 we observed. The hard X-ray spectral property and cutoff feature of 4U 0142+61 can help us understand the common properties and radiation mechanisms in different classes of magnetar candidates.

In fitting the average spectrum of AXP 4U 0142+61, three models are employed: a power law, bremsstrahlung and cutoff power law. 4U 0142+61 is not detected in CGRO/COMPTEL observations (den Hartog et al. 2008). Therefore, a power law without a high energy cutoff is inconsistent with upper limits from COMPTEL. The bremsstrahlung model can naturally produce a cutoff in the hard X-ray spectrum ($E_{\rm cutoff} \approx kT$). However, the bremsstrahlung model predicts a photon index of $\Gamma \sim 1$ below the cutoff energy for all sources. This is inconsistent with our current observations on available AXPs and SGRs (different sources have different photon indexes, Götz et al. 2006). Furthermore, the bremsstrahlung model assumes the process is in the form of a hot spot (e.g. the model of Thompson & Beloborodov 2005; Beloborodov & Thompson 2007). However, observationally 4U 0142+61 shows hard X-ray emissions in all phases (den Hartog et al. 2008). Therefore, the bremsstrahlung model is not favored on physical grounds. In our analysis of 4U 0142+61, the bremsstrahlung model has a reduced χ^2 of 4. Therefore, it is also not favored statistically. Combining the nonthermal nature of hard X-ray emissions from a magnetar and upper limits from COMPTEL, a cutoff power law is preferred for 4U 0142+61.

A cutoff power law for 4U 0142+61 results in a photon index of $\Gamma \approx 0.5$ and cutoff energy of $E_{\rm cutoff} \approx 130\,{\rm keV}$ (see Table 1). The photon index and cutoff energy have relatively large uncertainties. Future hard X-ray observations may provide more accurate measurements (e.g., by the *Hard X-ray Modulation Telescope, HXMT*). The present value of photon index and cutoff energy can give us some information about the hard X-ray emission mechanism in magnetars. A cutoff energy around $130\,{\rm keV}$ can rule out the emission mechanism involving ultra-relativistic electrons. The electron motion should be mildly relativistic (both microscopic and bulk motions).

The quantum electrodynamics model of Heyl & Hernquist (2005) predicts a cutoff energy much higher than $1\,{\rm MeV}$. This is inconsistent with the cutoff energy of 4U 0142+61. It also predicts a high energy gamma-ray flux detectable by *Fermi*-LAT. However, 4U 0142+61 is not detected by *Fermi*-LAT (Şaşmaz Muş & Göğüş 2010; Tong et al. 2010). Therefore, the quantum electrodynamics model can be ruled out with our current knowledge of magnetars.

The resonant inverse Compton scattering model by Baring & Harding (2007) involves ultra-relativistic electrons. It also predicts a cutoff energy much higher than $1\,{\rm MeV}$. Therefore, the ultra-relativistic scattering model is inconsistent with our observations. Resonant inverse Compton scattering involving mildly relativistic electrons is explored by Beloborodov (2013). It predicts a cutoff energy around $1\,{\rm MeV}$. However, the cutoff energy for 4U 0142+61 is around $130\,{\rm keV}$. Considering the uncertainty in cutoff energy due to the uncertainty in photon index (a larger photon index will result in a higher cutoff energy), we cannot rule out this model at present. However, the problem with Beloborodov (2013) is that the particles there are from a transient corona. The corresponding hard X-ray emissions will also be transient, with typical timescale for decay of around one year. The hard X-ray flux of 4U 0141+61 is stable over nine years as demonstrated in Section 4. Therefore, if the hard X-ray emission of 4U 0142+61 is produced by mildly relativistic electrons, the electrons must be from a persistent source.

AXPs and SGRs may be magnetars. At the same time they can also be neutron stars accreting from fallback disks (Tong & Xu 2011). The bulk motion of the accretion flow may also explain the hard X-ray emissions of 4U 0142+61 (Trümper et al. 2010). In the accretion case, the bulk motion of the accretion flow, the microscopic inverse Compton scattering and the resonant inverse Compton scattering[2] can all contribute to the hard X-ray emissions. A cutoff energy around $130\,{\rm keV}$ requires that both the bulk and microscopic motions of electrons should be at most mildly relativistic. Multiband observations of AXPs and SGRs may help us distinguish between the magnetar model and the accretion model. X-ray polarization observations may help us finally solve this problem.

Limited by the sensitivity of *INTEGRAL*/IBIS, there is large uncertainty in the cutoff energy due to the uncertainty in photon index, which may be better constrained by future observations. The *HXMT*[3], the first astronomical satellite to be launched by China, is a collimated hard X-ray telescope based on the direct demodulation method and NaI(Tl)/CsI(Na) phoswich detection techniques. The payload consists of three telescopes; they work in the low, middle and high energy ranges respectively, covering the 1–250 keV energy band. The high energy telescope is sensitive between 20 and 250 keV, and has a large collection area of 5000 $\rm cm^2$ which provides high sensitivity. Based on parameters describing the power law and cutoff power law models in Table 1, we simulate hard X-ray spectra of 4U 0142+61 with the *HXMT* response matrix and background file, as shown in Figure 5. With an integration time of 1 Ms, there is an obvious discrepancy between the two models below 30 keV and around 200 keV. We believe that future *HXMT* observations will be able to provide more accurate values for the photon index and cutoff energy, and verify the existence of a cutoff in 4U 0142+61.

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[2] The magnetic field required by the resonant inverse Compton scattering is only 10^{11}–10^{13} G (Beloborodov 2013). Therefore, it can also happen in the accretion case.

[3] For detailed information about this new mission, see the websites: *http://www.hxmt.org/english* and *http://heat.tsinghua.edu.cn/hxmtsci/book.html*

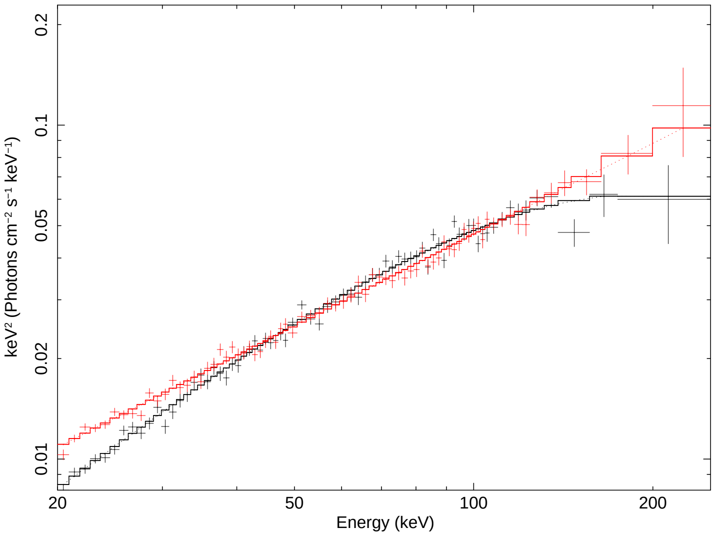

Fig. 5 Simulated spectra of 4U 0142+61 for *HXMT* based on parameters of the power law and cutoff power law models, shown in red and black respectively (*color online*).

6 CONCLUSIONS

In this work, we systematically studied the hard X-ray spectral properties of a typical anomalous X-ray pulsar 4U 0142+61, based on long-term monitoring of hard X-ray emission, by *INTEGRAL*. From 2003–2011, the 20–150 keV flux of 4U 0142+61 shows no significant variations. The derived hard X-ray luminosity of $\sim 10^{35}$ erg s^{-1} above 20 keV is also similar to the luminosity in soft X-ray bands of 1–10 keV. Though the total X-ray luminosity did not show variations, the hard X-ray spectral properties had some changes in the observed time intervals. If the spectra of 4U 0142+61 are fitted with a simple power law model, the photon index Γ changes from 0.7–1.6. These spectra are also fitted by a cutoff power law model, which gives $\Gamma \sim 0.3 - 1.5$ with cutoff energies $E_{\rm cutoff} \sim 110 - 250$ keV. To probe the high energy cutoff in the spectrum of 4U 0142+61, we collected all the data to obtain an average spectrum (with a higher significance level). A cutoff power law model is preferred in spectral fittings, suggesting there is a spectral cutoff around 130 keV. This is the first time that the high energy cutoff of this AXP is derived, which will help to understand mechanisms that produce high energy radiation in magnetars.

The detection of a high energy cutoff around 130 keV can exclude the resonant inverse Compton scattering model with ultra-relativistic electrons (Baring & Harding 2007). If the radiation still comes from magnetars, mildly relativistic electrons from persistent injections are required in the magnetar's magnetosphere. However, properties of the hard X-ray emission from 4U 0142+61 are still consistent with the accretion model, and the bulk and microscopic motions of electrons in the accreting flow should be mildly relativistic. Future observations of hard X-rays, especially multi-wavelength studies, will further help to resolve the magnetar and accretion models. At least the present simulation studies suggest that future *HXMT* observations can provide better constraints on the high energy cutoff of 4U 0142+61 and more AXPs. In the near future, a good understanding of hard X-ray spectral properties of AXPs and SGRs by *INTEGRAL* and *HXMT* observations will provide important clues to the nature and radiation mechanisms in magnetars.

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References

Baring, M. G., & Harding, A. K. 2007, Ap&SS, 308, 109
Beloborodov, A. M., & Thompson, C. 2007, ApJ, 657, 967
Beloborodov, A. M. 2013, ApJ, 762, 13
den Hartog, P. R., Kuiper, L., Hermsen, W., et al. 2008, A&A, 489, 245
Esposito, P., Mereghetti, S., Tiengo, A., et al. 2007, A&A, 476, 321
Enoto, T., Nakazawa, K., Makishima, K., et al. 2010a, ApJ, 722, L162
Enoto, T., Nakazawa, K., Makishima, K., et al. 2010b, PASJ, 62, 475
Hulleman, F., van Kerkwijk, M. H., & Kulkarni, S. R. 2000, Nature, 408, 689
Enoto, T., Makishima, K., Nakazawa, K., et al. 2011, PASJ, 63, 387
Goldwurm, A., David, P., Foschini, L., et al. 2003, A&A, 411, L223
Götz, D., Mereghetti, S., Tiengo, A., & Esposito, P. 2006, A&A, 449, L31
Heyl, J. S., & Hernquist, L. 2005, MNRAS, 362, 777
Kuiper, L., Hermsen, W., & Mendez, M. 2004, ApJ, 613, 1173
Kuiper, L., Hermsen, W., den Hartog, P. R., & Collmar, W. 2006, ApJ, 645, 556
Kuiper, L., Hermsen, W., den Hartog, P. R., & Urama, J. O. 2012, ApJ, 748, 133
Lebrun, F., Leray, J. P., Lavocat, P., et al. 2003, A&A, 411, L141
Mereghetti, S. 2008, A&A Rev., 15, 225
Rea, N., Nichelli, E., Israel, G. L., et al. 2007, MNRAS, 381, 293
Rea, N., Israel, G. L., Turolla, R., et al. 2009, MNRAS, 396, 2419
Rea, N., Esposito, P., Turolla, R., et al. 2010, Science, 330, 944
Şaşmaz Muş, S., & Göğüş, E. 2010, ApJ, 723, 100
Thompson, C., & Duncan, R. C. 1996, ApJ, 473, 322
Thompson, C., & Beloborodov, A. M. 2005, ApJ, 634, 565
Tong, H., Song, L. M., & Xu, R. X. 2010, ApJ, 725, L196
Tong, H., & Xu, R.-X. 2011, International Journal of Modern Physics E, 20, 15
Tong, H., & Xu, R. X. 2012, ApJ, 757, L10
Trümper, J. E., Zezas, A., Ertan, Ü., & Kylafis, N. D. 2010, A&A, 518, A46
Wang, W. 2008, in American Institute of Physics Conference Series, 968, Astrophysics of Compact Objects, eds. Y.-F. Yuan, X.-D. Li, & D. Lai, 101