Insight-HXMT Six-Year In-Orbit Background Review Postprint

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Abstract

We review the background of the Insight-Hard X-ray Modulation Telescope (Insight-HXMT) during its first 6 yr of on-orbit operation, including the geographical distribution, energy spectrum, temporal variation characteristics, and long-term evolution of the on-orbit background for each payload. In addition, we also review the estimation methods for the on-orbit background of each Insight-HXMT payload, and comprehensively introduce the background models for each payload and the accuracy of background estimation. Overall, the on-orbit background of Insight-HXMT meets expectations, and the background models for each payload can reliably estimate the energy spectrum and light curves of the on-orbit background.

Full Text

Preamble

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A Review of the First Six-Year In-orbit Background of Insight-HXMT

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Abstract

This paper reviews the in-orbit background of the Insight-Hard X-ray Modulation Telescope (Insight-HXMT) over the first six years of operation, encompassing the geographical distributions, spectral and temporal characteristics, and long-term evolution of the background for each payload. Additionally, we review the estimation methods for the in-orbit background of each Insight-HXMT payload and provide a comprehensive overview of the background models and their estimation accuracy. Overall, the in-orbit background of Insight-HXMT meets expectations, and the background models for each payload can reliably estimate both the spectral and temporal variations of the in-orbit background.

Keywords space vehicles: instruments, methods: data analysis, X-rays: background

1 Introduction

The Insight-Hard X-ray Modulation Telescope (Insight-HXMT) is China' s first general-purpose space X-ray telescope, launched on June 15, 2017, which has achieved fruitful scientific results in X-ray astronomy [1]. The observatory carries three main payloads: the Low Energy telescope (LE) [2], Medium Energy telescope (ME) [3], and High Energy telescope (HE) [4]. The coordinated operation of these three primary payloads provides Insight-HXMT with broad energy coverage, large effective area, and high time resolution. The main performance parameters of Insight-HXMT are listed in Table 1 .

Most of Insight-HXMT' s scientific results derive from pointed observations of Galactic X-ray sources [5, 6]. In these observations, the acquired data contain both physical signals from X-ray sources and background signals of varying proportions. To obtain reliable physical results, accurate background estimation becomes crucial. In addition to pointed observations of known Galactic X-ray sources, Insight-HXMT has two other primary missions: the Galactic plane scanning survey and gamma-ray burst all-sky monitoring. These two missions employ different observation strategies and consequently exhibit different background characteristics and estimation methods. For gamma-ray burst monitoring, background estimation is performed by averaging pre-burst and post-burst observations [7]; for the Galactic plane scanning survey, background signals are estimated by smoothing the data after removing the source' s modulated signal [8]. Compared to these two missions, background estimation for Insight-HXMT pointed observations is considerably more complex. As Insight-HXMT is a collimated telescope, it lacks the capability of imaging telescopes like XMM-Newton [9, 10] and Chandra [11] to directly obtain accurate backgrounds from images, nor does it employ the traditional on-off observation mode used by other collimated telescopes such as BeppoSAX/PDS [12, 13] and RXTE/HEXTE [14, 16]. Therefore, Insight-HXMT requires background estimation methods tailored to its specific characteristics. To enable more accurate background estimation, Insight-HXMT has developed dedicated background models based on its unique features [17, 19].

Insight-HXMT operates in a near-Earth circular orbit at an altitude of 550 km with an inclination of 43°. Previous studies [17, 22] have shown that the space environment in Insight-HXMT' s orbital region is complex, with various particles interacting with the satellite platform and payload instruments to produce multiple background components [23, 24]. Among these, cosmic ray protons contribute most significantly to the background, while electrons, neutrons, the Cosmic X-ray Background (CXB), and Earth albedo gamma rays also contribute. Insight-HXMT is equipped with a Particle Monitor (PM) on its top section to detect environmental protons (energy $E > 8$ MeV) and electrons (energy $E > 200$ keV) [25]. During the first six years of operation, the geographical distribution of PM count rates showed minimal variation across low-latitude regions, high-latitude regions, and the South Atlantic Anomaly (SAA). However, since 2022, enhanced solar activity has increased atmospheric density, leading to an overall decrease in PM count rates. While we observe some long-term variations in the Insight-HXMT background, these are not solely due to solar activity cycles but are largely related to radiation damage in LE and ME detectors and activation effects in HE from charged particle bombardment. Therefore, when reviewing Insight-HXMT' s background, we must examine both the evolution of its observational characteristics and the validity of the background models.

This paper comprehensively reviews the background of Insight-HXMT during its first six years in orbit. We use observations of blank sky fields at high Galactic latitudes to investigate the in-orbit background of Insight-HXMT' s three main payloads, including their observational characteristics and systematic error analysis of the background models. Table 2 presents detailed information about these blank sky observations. Notably, Insight-HXMT' s three telescopes have different field-of-view (FoV) sizes and orientations. Figure 1 [Figure 1: see original paper] and Table 1 show the orientation and parameters of these fields of view. For LE and ME pointed observations, the use of small FoV detectors is recommended for scientific analysis. Therefore, this paper focuses on the observational characteristics and background models of these detectors. The paper is organized as follows: Sections 2–4 describe the backgrounds of LE, ME, and HE, respectively, with summary and conclusions presented in Section 5.

2 Low Energy X-ray Telescope

LE consists of a series of Swept Charge Device (SCD) detectors with a geometrical area of 384 cm^2, covering an energy range of 0.7–13 keV. LE has three telescope boxes with 60° differences in their field-of-view directions. Each box contains 20 small FoV detectors (some of which have failed sequentially), 6 large FoV detectors, and 2 fully blocked detectors (with collimators sealed by aluminum caps). The blocked small FoV detectors are designed to measure particle backgrounds, while the blocked large FoV detectors are implanted with ^{55}Fe radioactive isotopes to monitor energy response. During Insight-HXMT' s first six years of operation, some LE detectors have failed and been turned off. Detailed information about LE' s failed detectors can be obtained from the "bad detector FITS files" included in the Insight-HXMT data analysis software. Figure 2 [Figure 2: see original paper] shows the light curve of a blank sky field, displaying typical LE background profiles and characteristic features. The entire time range can be divided into anomalous and normal instrument phases. During anomalous phases, LE is typically disturbed by numerous low-energy charged particles and visible light due to its relatively large field of view, making accurate estimation difficult. In severe cases, LE detectors saturate due to on-board storage overflow. Normal instrument phases can be categorized into three types: Earth occultation intervals, during which light curves from detectors with different fields of view coincide and no CXB photons are recorded; “count rate burst” periods, which are detected by both small and large FoV detectors with flux roughly proportional to field-of-view size; and Good Time Intervals (GTIs), which are periods without Earth occultation or count rate bursts and are typically used for scientific analysis. To accurately estimate backgrounds, the background analysis software must perform both routine GTI selection and comparison of count rates between small and large FoV detectors [17]. Below we present the observational characteristics of LE backgrounds and the validity of background models during the first six years.

2.1 Observational Characteristics and Long-term Evolution of LE Background

Figure 3 [Figure 3: see original paper] compares the geographical distributions of LE backgrounds before and after June 30, 2020. The distribution across geographic longitude and latitude remains unchanged, but the intensity increases significantly. Figure 4 [Figure 4: see original paper] (left panel) shows background spectra from small FoV detectors at the same geographic location. The low-energy end of the spectrum shows minimal variation, while the high-energy end exhibits more pronounced evolution. During the first four years, the high-energy background level gradually increased due to equipment radiation damage (details below). From the fifth year onward, the high-energy background level decreased due to reduced charged particle levels in the satellite’ s orbit. Various spectral lines in the background spectrum become increasingly less prominent and difficult to visually identify because of their low equivalent width and continuous broadening with decreasing LE energy resolution. Details about background spectral lines (e.g., energy, broadening) and detector information can be found in works on Insight-HXMT’ s in-orbit operation and calibration [26]. As demonstrated by ground simulations [22] and previous in-orbit observations, the LE background can be simplified into diffuse X-ray background dominating at low energies and particle background dominating at high energies. Therefore, the differences between the two geographical distributions shown in Figure 3 are mainly due to high-energy variations. Figure 4 (right panel) shows background spectra from blocked detectors over the first six years, consistent with results from small FoV detectors. As described by Zhang et al. [22], Insight-HXMT’ s background can be produced by various incident particles. Background recorded immediately after incidence is called prompt background, while background recorded long after incidence (hours to months) is called delayed background. Notably, backgrounds caused by CXB and cosmic ray protons are both prompt backgrounds. The LE background light curve shows minimal variation during the first six years, with the most obvious feature being stable count rates at low energies and significant modulation by Earth' s magnetic field at high energies, as also shown in Figure 2.

The spectral shape of LE blocked detectors does not change with geographic location and can be used to characterize the particle background spectral shape of small FoV detectors [17]. The LE background model utilizes this feature to provide simple and reliable background estimation. Although the LE background evolved during the first six years, the changes were not extremely significant (Figure 3). Figure 4 shows that small and blocked FoV detectors exhibit similar evolutionary trends: as in-orbit time increases, the lower limit of the spectral energy range becomes higher and count rates increase accordingly. For LE detectors, large signals can be recorded simultaneously in several pixels as split events. However, only events above a certain threshold are recorded and participate in subsequent split event reconstruction. For example, a large signal with energy E can be recorded as two signals with energies E_0 and E_1 ($E_0 + E_1 = E$). If E_1 is below the threshold, this large signal will be treated as a single event with energy E_0. As radiation damage to LE detectors increases, the noise signal distribution becomes broader. To eliminate the impact of noise signals on the operational energy range, the threshold is adjusted higher. This raises the low-energy limit of LE detectors, as shown in the low-energy portion of the spectra in Figure 4. Additionally, small signals that could be recorded and participate in split event reconstruction before threshold adjustment will not exceed the threshold afterward, meaning previously reconstructible double events will no longer be reconstructed after threshold adjustment. As the threshold increases, a larger proportion of double events will not be reconstructed and will instead be treated as single events with lower energy. As shown in Figure 4, the evolutionary trend of the background spectrum during the first four years is an annual leftward shift at the high-energy end. Therefore, the increasing trend of LE high-energy background during the first four years is essentially the result of LE detector radiation damage. Furthermore, the spectrum of blocked detectors at high energies may be mixed with above-threshold signal peaks, so the effective energy range for blocked detectors in the background model must be adjusted accordingly.

2.2 LE Background Model

The validity of background models must be examined as it is crucial for scientific analysis. Following previously developed methods [17], we perform background estimation for each blank sky observation. Figure 5 [Figure 5: see original paper] shows an example of background spectrum estimation. Background model parameters are updated annually to maintain estimation accuracy, and systematic errors of the background model are investigated. Figure 6 [Figure 6: see original paper] displays the systematic errors in different energy bands between 2-10 keV for each year since Insight-HXMT' s launch. The results show no significant change in systematic errors compared to the first two years after launch, indicating that the background model is stable and can provide accurate background estimation. However, since data around 1.5 keV are frequently affected by electronic noise and the detection threshold has been raised, this paper presents systematic errors only above 2 keV.

3 Medium Energy X-ray Telescope

As shown in Table 1, ME is a collimated telescope covering the 5–40 keV energy range, with a total geometrical area of 952 cm^2. It consists of 54 detectors, each containing 32 Si-PIN pixels. Each of the three boxes contains 18 detectors: 15 with small FoV collimators, two with large FoV collimators, and one with a fully blocked collimator for background estimation. ME background characteristics share some similarities with LE at high energies, particularly in light curve features and geographical distribution. However, the proportions of different background components differ significantly, with particle background dominating throughout the entire energy range [19, 22].

Figure 7 [Figure 7: see original paper] compares the geographical distributions of ME backgrounds in the first and sixth years. The ME background in the sixth year is slightly higher than in the first year. In regions near the SAA ($330° < lon < 360°$, $0° < lat < 30°$), the background is significantly higher than in most other regions at similar latitudes. This indicates that when the satellite passes through high particle flux regions (e.g., SAA), the ME background first increases and then decreases over time, demonstrating that ME background has delayed components. By comparing geographical distributions between ascending (south-to-north) and descending (north-to-south) orbital phases (Figure 7), we find that ME background has relatively strong short-timescale delayed components that contribute to its long-term evolution. ME background shows a clear anti-correlation with geomagnetic cutoff rigidity [19]. The evolution of ME background, particularly the intensity of the silver line, must be carefully handled to ensure background model accuracy.

Figure 8 [Figure 8: see original paper] shows the background light curves of ME small FoV detectors in six energy bands, revealing clear orbital modulation. A prominent peak caused by particle events appears in the light curves, typically occurring at high latitudes, with corresponding times excluded from GTIs. Figures 9 Figure 9: see original paper–(b) display spectral variations of small FoV detector backgrounds within the geographic region ($340° < lon < 350°$, $5° < lat < 15°$). First, the background level in ascending phase is much higher than in descending phase due to short-decay-timescale delayed background components, as the satellite has just left the SAA at this geographic location. During the first five years, ME background levels slowly increased over time due to cumulative effects from in-orbit operation, representing the accumulation of weak delayed components. In the sixth year, background levels decreased due to reduced charged particle levels in the satellite’ s orbit. The center of the silver line also shifted over time, indicating changes in the energy-channel relationship. Figures 9(c)–(d) show spectral evolution of blocked detectors. The silver line position did not shift significantly, indicating that blocked detectors experienced less radiation damage than small FoV detectors.

3.1 Observational Characteristics and Long-term Evolution of ME Background

The ME background spectral shape remains nearly unchanged across different geomagnetic cutoff rigidity ranges, but background levels vary significantly. ME background evolution, particularly the intensity of the silver line, requires careful treatment to ensure background model accuracy.

3.2 ME Background Model

We previously constructed an ME background model and corresponding database [19]. Since ME background spectral shape varies little with geographic location but more than LE' s, the background model must account for ME background at each geographic location for each detector. In each background estimation, we first use the database to obtain preliminary predicted background spectra for ME small FoV and blocked detectors at each geographic location the satellite passes, then further correct them using observations from blocked detectors. The ME database produces time-averaged, normalized background spectra for each geographic location, while blocked detectors determine the particle intensity at the time for model correction.

Backgrounds for all blank sky observations are estimated using model parameters for the corresponding year. Figure 10 [Figure 10: see original paper] shows an example of background estimation for a blank sky observation. Statistical analysis of all background estimation residuals yields systematic errors for each energy band [19]. Figure 11 [Figure 11: see original paper] displays systematic errors for six energy bands each year. The results show no significant increasing trend in systematic errors during the first five years. Systematic errors in the 10–15 keV band are relatively large, averaging about 2%, while errors in the 10–40 keV band are about 1.6%. In the sixth year, systematic errors above 15 keV increased but remain below 2.5% in all bands, indicating that the ME background model remains reliable.

4 High Energy X-ray Telescope

HE comprises 18 NaI(Tl)/CsI(Na) phoswich detectors (numbered DetID = 0, 1, 2, ···, 17), surrounded by 18 anti-coincidence detectors (ACDs) for active background shielding. Among these 18 detectors, 15 have small FoV, two have large FoV, and one has a fully blocked FoV for background estimation. Ground simulations indicate that NaI and CsI crystals can be activated by charged particles around Insight-HXMT' s orbit, and radioactive decay of activated crystals is the main source of HE background. As the satellite operates continuously in orbit, crystals in HE detectors are constantly activated. Background levels increased significantly during the first year of operation, with the increasing trend gradually slowing thereafter [20, 21].

4.1 Observational Characteristics and Long-term Evolution of HE Background

Figure 12 [Figure 12: see original paper] shows the geographical distributions of HE background in the first and sixth years. Overall distribution differences are small, but background count rates in the sixth year are significantly higher than in the first year. Unlike LE and ME backgrounds, HE background is dominated by delayed components due to crystal activation by charged particles. Therefore, backgrounds can differ substantially between ascending and descending orbital phases even at the same geographic location. Figure 13 [Figure 13: see original paper] displays background spectra for each year in both orbital phases at different geographic locations. Spectra at location $(lon, lat) = (345°, 15°)$ are shown in subplots (c) and (d). In ascending phase, when the satellite passes through the SAA, detector crystals become severely activated. Without sufficient time for decay, background levels are relatively high. In descending phase, however, the background is lower because considerable time has passed since the satellite last traversed the strong charged particle region, making the background dominated by long-timescale decay components. HE background spectra at different geographic locations show long-term evolution. The evolution shown in subplot (d) is less significant compared to other subplots because the satellite has just passed the SAA, so a large fraction of the background is contributed by short-timescale components. Additionally, charged particle intensity in the SAA did not change significantly over the six years. As described in previous works [20, 21], HE background spectra consist of various emission lines caused by interactions between detectors and high-energy particles. Figure 13 shows that spectral shapes remained stable over the six years.

Figure 14 [Figure 14: see original paper] shows light curves of blank sky observations in six different energy bands. In each band, background intensity rises to high levels when the satellite has just passed the SAA, then gradually decays with significant geomagnetic modulation. Differences exist between energy bands because the background comprises many components with different proportions, spectral shapes, and characteristic variation timescales.

4.2 HE Background Model

Based on HE background characteristics, we developed an HE background model [18]. Its principle is similar to ME' s but more complex. To obtain backgrounds at any geographic location and time, we constructed empirical functions with time as the independent variable to describe the long-term evolution of HE background. Preliminary background estimates can be obtained using orbital parameters and observation times, with further corrections made using data from blocked detectors. Therefore, HE background estimation heavily relies on the mathematical description of long-term background evolution, making the accuracy of empirical functions crucial for background estimation.

Figure 15 [Figure 15: see original paper] shows the long-term evolution of background count rates in the 46–74 keV range at six different geographic locations, demonstrating effects from different geomagnetic cutoff rigidities and different SAA delayed backgrounds. For each energy channel, the long-term evolution can be described by a broken line with several slopes. The fitted curve is formed by merging broken lines with different break times across this energy range, showing smooth transitions without obvious jumps. We chose broken-line functions to describe the long-term evolution of background count rates with time. While other functions might be acceptable, broken lines already describe the observational data well. As predicted by ground simulations [20, 21], activated isotopes cause rapid background count rate decay after each SAA passage, with long-term accumulation as in-orbit operation days increase. This accumulation rises rapidly during the initial post-launch period and becomes slower after hundreds of days because long-half-life isotopes are not dominant. This predicted long-term evolution is consistent with observational results shown in Figure 15. Notably, HE background shows a decreasing trend in the sixth year, resulting from increased orbital atmospheric density due to enhanced solar activity.

Using the background model, we can estimate backgrounds for all blank sky observations. Figure 16 [Figure 16: see original paper] shows an example of background estimation for a blank sky observation. Following methods introduced in previous work [18], systematic errors in different energy bands can be obtained. Figure 17 [Figure 17: see original paper] displays systematic errors for eight energy bands each year. The results show that average systematic errors each year are less than 3%, with no significant difference from results during the satellite’ s first two years of operation, indicating that the HE background model remains effective.

5 Summary and Conclusions

After six years of in-orbit operation, the backgrounds of Insight-HXMT’ s three telescopes show different evolutionary trends compared to the initial operation period. The main background features (temporal variation, spectral shape, and long-term evolution) are all consistent with design expectations.

To address radiation damage issues, LE detectors underwent a series of operations that also caused background changes. For example, detection thresholds were raised to avoid noise signals, whose distribution broadened with increasing radiation damage. Additionally, the continuous broadening of emission lines in background spectra results from degraded LE energy resolution. As in-orbit operation time increases, ME background levels increase due to accumulation of weak delayed components. Furthermore, ME background at low energies may be affected by low-energy noise in some pixels. Crystals in HE detectors are continuously activated, causing significant background intensity increases over time. During the first five years, the HE background growth trend gradually slowed and showed saturation behavior; in the sixth year, HE background exhibited a decreasing trend due to increased orbital atmospheric density from enhanced solar activity. Inconsistent background evolution at different energies means that background spectral shapes at certain geographic locations also evolve over time.

Although temporal evolution characteristics of LE and ME backgrounds are not significant, background model parameters must be updated annually to maintain estimation accuracy. For the HE background model, temporal evolution was considered from the beginning of model construction. Statistical analysis shows that systematic errors for all three telescopes changed little during Insight-HXMT' s first six years of operation, so the background models remain valid and reliable.

As described in previous work [17], the LE background model constructed using blank sky observations can effectively estimate both particle background and diffuse X-ray background caused by CXB, making it suitable for background estimation in pointed observations at high Galactic latitudes ($|b| > 10°$). To accurately estimate diffuse backgrounds in low Galactic latitude regions, the diffuse X-ray background obtained from Galactic plane scanning should be used in LE background estimation [27].

Notably, the current background models for all three telescopes rely heavily on blocked detectors. Therefore, blocked detectors are crucial, particularly for HE which has only one blocked detector. This poses a potential risk for background estimation due to insufficient redundancy. Consequently, an alternative background estimation approach independent of blocked detectors must be planned in advance, such as using ACD and PM as prompt particle monitors for LE and ME background estimation. For HE, a parameterized background model independent of blocked detectors has already been established [28]. By considering various physical factors contributing to HE background, a mathematical model accounting for these physical processes has been successfully constructed.

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