Insight-HXMT Six-Year Galactic Plane Scanning Survey: Broad X-ray Energy Band Monitoring Source Catalog Postprint

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Date: 2025-08-19T00:00:00+00:00

Abstract

We review the 6-year Galactic plane scanning survey of Insight-HXMT (Hard X-ray Modulation Telescope), focusing on the monitoring and analysis of known X-ray sources in the Galactic plane. During the first 6 years of Insight-HXMT' s on-orbit operation, it conducted over 3000 scanning observations of the Galactic plane in the broad energy band of 1–100 keV, with total observation time accounting for approximately 1/4 to 1/3 of Insight-HXMT' s total observation time. Long-term flux monitoring was performed for over 1300 different types of X-ray sources (detecting X-ray signals from more than 200 of these sources), and the monitoring results were compiled and analyzed, including the activity and spectral characteristics of different types of sources. We first introduce the data characteristics and analysis methods of Insight-HXMT satellite scanning observations (direct demodulation imaging and light curve fitting), then provide an overall description of the monitoring results from the Insight-HXMT scanning survey, and finally present statistical analyses of the properties of the monitored sources, such as spatial distribution characteristics, variability activity analysis, and hardness ratio analysis.

Full Text

Preamble

Vol. 66 No. 4

July 2025

Acta Astronomica Sinica Vol. 66 No. 4 Jul., 2025 doi: 10.15940/j.cnki.0001-5245.2025.04.004

Catalog of Wide X-ray Energy Band Monitoring Sources in the 6-yr Galactic Plane Scanning Survey of Insight-HXMT

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Abstract

We review the six-year Galactic plane scanning survey of the Insight-HXMT (Insight Hard X-ray Modulation Telescope), focusing on the monitoring results and analysis of known X-ray sources on the Galactic plane. During the first six years of its orbital operation, Insight-HXMT spent approximately one-quarter to one-third of its total observation time conducting over 3000 scanning observations of the Galactic plane in the wide energy range of 1–100 keV. Long-term flux monitoring was carried out for more than 1300 different types of X-ray sources (detecting X-ray signals from approximately 200 celestial bodies), and the monitoring results were compiled and analyzed, including the activity and spectral characteristics of different types of celestial objects. This paper first introduces the data characteristics and data analysis methods of the Insight-HXMT scanning observations (direct demodulation imaging and light curve fitting), then provides an overall description of the monitoring results of the Insight-HXMT scanning survey, and finally presents a statistical analysis of the nature of the monitored sources, such as spatial distribution characteristics, variability activity analysis, and hardness ratio analysis.

Key words space vehicles: instruments, methods: data analysis, X-rays: survey

1 Introduction

The Hard X-ray Modulation Telescope (Insight-HXMT) is China' s first general-purpose space astronomy satellite, launched on June 15, 2017 [1]. The Galactic plane scanning survey is one of Insight-HXMT' s primary scientific missions, accounting for approximately one-quarter to one-third of the total observation time, aiming to search for new transient phenomena and monitor known variable sources in the wide X-ray energy band. According to previous surveys by other international X-ray telescopes such as ROSAT (Roentgen Satellite), INTEGRAL (International Gamma-Ray Astrophysics Laboratory), Swift, and MAXI (Monitor of All-sky X-ray Image), most hard X-ray sources on the Galactic plane are variable, primarily various types of X-ray binaries [2–3]. Insight-HXMT' s narrow field-of-view design and large effective area across its detection energy bands provide advantages for surveying weak signals and variable sources. Insight-HXMT carries three main payloads: the Low Energy X-ray Telescope (LE, 0.7–13 keV), the Medium Energy X-ray Telescope (ME, 5–40 keV), and the High Energy X-ray Telescope (HE, 20–250 keV). LE consists of three detector boxes, each containing eight detector modules with a total of 96 SCD (Swept Charge Device) detectors [4]. ME comprises three detector boxes with Si-PIN detector arrays [5]. HE consists of 18 NaI(Tl)/CsI(Na) scintillator detectors [6]. All are collimated telescopes composed of three groups of small field-of-view detectors with 60° angles between them [1]. Each small field-of-view contains one LE box, one ME box, and five HE detectors. Additionally, the large field-of-view detectors can be used as a supplement for scientific data analysis and background estimation [7]. Due to the relatively narrow field of view, the small field-of-view detectors can obtain more accurate source fluxes and positions than the large field-of-view detectors during scanning observations, so we use only the small field-of-view detectors in the Galactic plane scanning survey [8].

During its six-year Galactic plane scanning survey, Insight-HXMT achieved comprehensive and deep coverage of the Galactic plane. Figure 1 [Figure 1: see original paper] shows the six-year cumulative exposure map and sensitivity map for the low-energy telescope. The optimal cumulative sensitivities achieved by the three telescopes across the entire Galactic plane over six years are (LE, 2–6 keV), (ME, 7–40 keV), and (HE, 25–100 keV). Insight-HXMT conducted long-term flux monitoring for more than 1300 different types of X-ray sources, detecting X-ray signals from approximately 200 celestial bodies and obtaining their long-term light curves across multiple energy bands between 1–100 keV. We performed statistical analyses of the activity and spectral characteristics of different types of celestial objects using this long-term monitoring data [9–10]. In this paper, we review the Insight-HXMT Galactic plane scanning survey focusing on the wide X-ray energy band monitoring source catalog. Section 2 introduces the data and analysis methods. Section 3 describes the wide X-ray energy band monitoring source catalog. The analysis of the source catalog is presented in Section 4. Finally, Section 5 provides a summary.

2 Scanning Data and Analysis Methods

In the Insight-HXMT Galactic plane scanning survey, the entire Galactic plane (Galactic longitude range: , Galactic latitude range:) is divided into dozens of regions of equal radius. To achieve complete coverage of the Galactic plane without gaps, there is overlap between adjacent regions. Due to Sun angle constraints ( ), each region is observable for approximately half a year. For each scanning region, observations are conducted using a line-by-line scanning pattern as shown in Figure 2 [Figure 2: see original paper].

Three scanning speeds (, ,) and ten scanning intervals ( ) are available for scanning observations. Two scanning region radii ( ) are used. The duration of a single scanning observation is typically 2–3 hours, depending on the scanning parameters. For scanning observations with , the duration is approximately 3.3 hours.

Figure 3 [Figure 3: see original paper] shows the data analysis processing flow for Insight-HXMT satellite data. Following the steps shown in Figure 3, we use the Insight-HXMT data analysis software HXMTsoft to process the raw data, including basic processing, background subtraction, and obtaining net light curve data. Details of the data processing can be found in the works of Sai et al. [8] and Wang et al. [9–10].

Figure 4 [Figure 4: see original paper] shows a net light curve from a single LE scan, where complex modulation signals can be seen. When the telescope' s field of view sweeps across an X-ray source, the source leaves a modulation signal because the point spread function (PSF) of a collimated telescope is a function of position. There are multiple methods to handle these modulation signals, each with different advantages, but the accuracy of all results depends on the precision of PSF calibration. Due to collimator deformation caused by the satellite platform and detector design, as well as various factors during satellite launch and in-orbit operation, the PSF of each Insight-HXMT telescope cannot be simply determined by the collimator' s geometric parameters.

Therefore, we calibrate the average PSF of each Insight-HXMT payload collimator annually. The basic approach is to add rotational and two-dimensional effective area corrections to the geometric model of the collimator PSF. The geometric model of the collimator PSF, i.e., the detection efficiency at position (,) in the field of view, can be expressed as:

$$P(\theta,\phi) = C \cdot \left[1 - \frac{|\tan\theta|}{\tan\theta_0}\right] \cdot \left[1 - \frac{|\tan\phi|}{\tan\phi_0}\right] \cdot \frac{1}{\sqrt{\tan^2\theta + \tan^2\phi + 1}}; \qquad (1)$$

where and are the ranges of the field of view in the long and short directions, respectively, and is the detection efficiency at the center of the field of view (,). Details of the PSF for each Insight-HXMT detector and the detailed PSF correction process can be found in the work of Nang et al. [11].

In our work, we primarily employ two methods to analyze Insight-HXMT scanning data: direct demodulation imaging and light curve PSF fitting. The direct demodulation method can image the scanned sky area with very intuitive results, while light curve fitting provides accurate flux and error information. The combination of these two methods ensures the accuracy and reliability of Insight-HXMT scanning data analysis results. Both methods are described below.

2.1 Direct Demodulation Imaging

The direct demodulation method is a high-resolution, high-precision imaging method proposed by Chinese scholars Li Tibei and Wu Mei in the 1990s [12–13]. It solves the observation equation system describing the observation process through iterative direct solution, introducing physical constraints during the iteration process to avoid ill-posedness and oscillations caused by incomplete observation data and low signal-to-noise ratios. Therefore, the iterative results achieve both high spatial resolution of direct demodulation and good convergence with real physical meaning. This method has been successfully applied to image reconstruction for various X-ray astronomy satellites and possesses strong imaging and spectral deconvolution capabilities.

The direct demodulation method is one of the main reconstruction algorithms adopted for Insight-HXMT Galactic plane scanning data analysis. Using it to process Galactic plane scanning data can obtain position and intensity information for numerous celestial sources, enabling flux monitoring of celestial sources and discovery of transient sources. Figure 5 [Figure 5: see original paper] shows the reconstruction results for the Galactic Center region using the direct demodulation method, with positioning accuracy better than 8 [1]. Since the applicable scope of the direct demodulation method is image reconstruction of stable sources, this condition is generally satisfied. For example, the outburst timescales of many variable sources in the Galactic plane are on the order of weeks to months, which is much longer than the duration of a single Insight-HXMT Galactic plane scan (approximately 3 hours). Therefore, these sources can be considered stable during the 3-hour scan, and the direct demodulation method is suitable for processing most Galactic plane scanning data.

However, because there are variable sources with shorter timescales in the Galactic plane, such as Type II bursts with timescales of seconds, these cannot be treated as stable sources. Therefore, it is necessary to improve the direct demodulation method to make it applicable to image reconstruction of short-timescale variable sources. To this end, we have developed a time-dependent direct demodulation method [14]. By modifying the imaging equation to incorporate short-timescale structures and their responses, we obtain a time-dependent imaging equation and derive the iterative solution formula for this equation through formula derivation. The improved direct demodulation method can provide accurate light curves of short-timescale variable sources within the scanning exposure time and improve the positioning accuracy of variable sources.

Using the time-dependent direct demodulation method to reconstruct the Type II bursts discovered by Insight-HXMT in the Rapid Burster MXB 1730-335 (burst duration s, burst interval s), the bursts of the Rapid Burster MXB 1730-335 can be well reproduced. Figure 6 [Figure 6: see original paper] (left) shows its fine flux monitoring curve. The burst frequency is 2 times per minute, consistent with the relaxation oscillator phenomenon mentioned in the literature, i.e., the positive correlation between the fluence of each burst peak and the time to the next peak shown in Figure 6 (right).

The time-dependent direct demodulation method has great application prospects in the detection of short-timescale variable signals, particularly providing strong technical support for Insight-HXMT' s detection of Supergiant Fast X-ray Transients (SFXTs). The typical outburst timescale of these transients is only a few hours, with light curves showing fast rise and slow decay characteristics, and flux variations reaching times the quiescent level. Based on Monte Carlo simulations, we simulated Insight-HXMT' s observation of an SFXT and then used the time-dependent direct demodulation method to reconstruct the simulated data. The reconstruction results shown in Figure

7 [Figure 7: see original paper] clearly reproduce the fast rise and slow decay outburst characteristics of the SFXT, with reconstructed intensity parameters matching the input values and improved positioning accuracy. In this simulation example, the positioning accuracy is 0.6 . Currently, only about a dozen supergiant fast X-ray transients have been discovered, and their outburst mechanisms remain unclear. Approximately three models have been proposed to explain this rare flaring phenomenon: clumpy stellar winds, eccentric orbital motion of companion stars, and transitions in accretion selection mechanisms [15-16]. If Insight-HXMT can discover more SFXTs through Galactic plane scanning, it can provide observational clues and test evidence for theoretical models.

2.2 Light Curve PSF Fitting

In the analysis of Insight-HXMT scanning data, we employ PSF models to directly fit the light curves from different fields of view to obtain the positions and flux information of scanned sources, with the overall process shown in Figure 8 [Figure 8: see original paper]. During PSF fitting, we first identify sources covered by the field of view based on effective area, and then fit their flux information. To improve fitting efficiency and accuracy, we first distinguish the fluxes of these sources as strong or weak, defining strong sources as those with fluxes above the satellite sensitivity (contributing significantly to the light curve), and weak sources as the opposite. We then jointly fit all strong sources to obtain flux information for each strong source. After completing the strong source fitting, we use residuals to search for new source candidates, which aims to identify potentially existing but unconfirmed sources. Finally, we adopt a single PSF model fitting strategy for all weak sources entering the field of view to ensure no coupling occurs during fitting and to avoid wasting substantial computational resources.

Figure 9 [Figure 9: see original paper] shows an example of Insight-HXMT scanning data analysis. The three blue light curves in Figure 9 (a) represent the background-subtracted light curves of three boxes during good time intervals. The red curve represents the final fitting result. To further evaluate the fitting quality, there is a corresponding gray line below each blue curve showing residuals, which display the differences between the fitting results and observational data. Figure 9 (b) shows the corresponding satellite scanning track, where the purple line represents the satellite trajectory during good time intervals, blue scatter points indicate weak sources passed by the scanning field of view during this scan, and red five-pointed stars represent strong sources in this observation, each marked with a serial number.

3 Overview of Survey Results

Insight-HXMT conducted more than 3000 scanning observations during its six-year Galactic plane scanning survey, obtaining a large amount of scanning observation data. Following the processing flow described in Section 2, each scanning dataset undergoes direct demodulation imaging and light curve fitting to obtain position and flux information for scanned sources. Insight-HXMT monitored 1336, 957, and 935 known sources in 1-6 keV, 7-40 keV, and 25-100 keV, respectively. We compiled the monitoring results into a monitoring source catalog, which mainly includes the following information for each energy band: (1) source name, (2) source coordinates, (3) source type, (4) source flux and error, (5) variability amplitude and error, and (6) hardness ratio and error. Among all monitored sources, 223 sources were detected with signal-to-noise ratio S/N > 5 in 2-100 keV, and 33 sources were detected with significant signals in all three payloads. Figure 10 [Figure 10: see original paper] shows the positions of Insight-HXMT scanning monitoring sources in Galactic coordinates. By statistically analyzing the relationship between signal-to-noise ratio and flux for all monitored sources in each scanning observation, we can estimate the limiting sensitivity of a single Insight-HXMT scan. The systematic errors of the scanning can be estimated through the fluctuations in the long-term light curve of Crab [8, 11]. The detection results of Insight-HXMT in different energy bands and the properties of the detectors are listed in Table 1 .

4 Basic Analysis of the Monitoring Source Catalog

This section is primarily based on the statistical analysis work of Wang et al. on the first four years of Insight-HXMT scanning results [9–10], presenting multidimensional statistical displays of the monitoring results for 223 bright sources in the Insight-HXMT monitoring source catalog, focusing on the activity, variability characteristics, spectral characteristics, and spatial distribution of different types of celestial objects.

4.1 Variability Amplitude of Bright Sources in the Monitoring Catalog

Long-term monitoring curves of various X-ray sources in different energy bands are one of the important scientific outputs of Insight-HXMT. Different types of sources show different levels of activity in long-term light curves. We use to quantify their variability amplitude, with the formula as follows:

$$F_{\text{rms}} = \sqrt{S^2 - \langle\sigma^2\rangle}/\langle f\rangle; \tag{2}$$

where is the average of the long-term flux, represents the average of the squares of the long-term flux errors, denotes the best-fit flux of the source in the i-th scan, and is the number of scanning monitoring data points. A larger value indicates greater flux variation of the source during the monitoring period. The error of can be calculated by:

$$dF_{\text{rms}} = \sqrt{\left(\sqrt{2/N}\cdot\langle\sigma^2\rangle/\langle f\rangle^2\right)^2 + \left(\sqrt{\langle\sigma^2\rangle/N}\cdot 2F_{\text{rms}}/\langle f\rangle\right)^2}. \tag{4}$$

A source is defined as flux-stable in the corresponding energy band if its is less than or equal to that of Crab in that energy band; otherwise, it is a variable source. Figure 11 [Figure 11: see original paper] shows the distribution histogram of for 223 sources, with the horizontal and vertical axes representing the values and number of sources, respectively. Each subplot represents a different energy band. The median of each type of source (marked on each subplot) is used to indicate the overall trend. The figure shows that the flux of High-Mass X-ray Binaries (HMXBs) is more active than that of Low-Mass X-ray Binaries (LMXBs) in any energy band. In 2-6 keV and 7-40 keV, the flux of Black Hole Binaries (BHBs) varies more than that of Neutron Star Binaries (NSBs). Additionally, the of LMXBs, NSBs, and BHBs shows a decreasing trend with increasing energy band. The fluxes of Supernova Remnants (SNRs), isolated pulsars, and Seyfert 1 galaxies are more stable than those of X-ray binaries. However, some sources among these three types also have relatively large , possibly due to their low average flux.

4.2 Variability of Different Types of Binary Systems in the Monitoring Catalog

We analyzed the flux variations of 32 X-ray binaries detected in all three detectors. Figure 12 [Figure 12: see original paper] shows the distribution of for these sources in three energy bands. As shown in Figure 12 (a), the values of 15 Neutron Star Low-Mass X-ray Binaries (NS-LMXBs) in 2-6 keV are lower than those in 7-40 keV or 25-100 keV. Figure 12 (c) shows that the median of LMXBs gradually increases with energy band. This is consistent with the study by Mitsuda et al. in 1984 [18]: the spectrum of NS-LMXBs consists of multi-temperature blackbody radiation from optically thick accretion disks and blackbody radiation from the neutron star surface, with the former being stable and the latter showing active variations. However, HMXBs show the following characteristics: (1) Compared with LMXBs in the three energy bands, HMXBs show more active flux variations in all three energy bands; (2) The of NS-LMXBs in each energy band is lower than that of BH-HMXBs, and the of BH-LMXBs in each energy band is lower than that of BH-HMXBs; (3) With increasing energy band, the of NS-HMXBs shows a trend of first increasing and then decreasing. These variations may be related to the selected energy bands but may also be related to the accretion processes in HMXBs. Depending on the companion star, HMXBs can be divided into three subclasses: (a) Be/X-ray binaries; (b) supergiant X-ray binaries; (c) supergiant fast X-ray transients. Since different subclasses have different ways of accreting material from companion stars, this may also lead to more diverse outburst patterns.

4.3 Activity Level and Flux, Spectrum, and Spatial Distribution of Bright Sources

We calculated and analyzed the hardness ratios (HR) of bright sources in the catalog under different combinations of high and low energy bands. HR can be defined as the ratio of flux in high energy band to that in low energy band. Since different radiation mechanisms produce photons in different energy bands, HR is often used to reflect the spectral characteristics of X-ray sources. In this work, we first divided bright sources into flux-stable (FS) and flux-variable (FV) groups based on their flux stability, and then further divided them into spectrum-stable (SS) and spectrum-variable (SV) groups based on spectral stability. Thus, all bright sources are ultimately divided into three activity levels: , , and sources. Table 2 shows the number of sources with these three activity levels under different combinations of high and low energy bands. When judging flux stability, if a source' s 1-σ lower limit of is greater than Crab' s , the flux is considered variable; otherwise, it is considered stable. When judging spectral stability, we compare it with Crab' s long-term HR stability using a standard chi-square test.

A source is considered to have an active spectrum in the target energy band if its chi-square value is greater than the limit at the corresponding degrees of freedom; otherwise, it is considered spectrum-stable. This limit is obtained using the chi-square of Crab' s long-term HR in the corresponding high and low energy bands. Figure 13 [Figure 13: see original paper] shows the long-term light curves and HR of Crab, Cen X-3, and Cyg X-1. The degrees of freedom and chi-square for Crab' s long-term HR are 78 and 77.3, respectively, corresponding to a significance level of 0.5, which is therefore used to determine the flux activity level of other bright sources in these two energy bands. The degrees of freedom for Cen X-3 and Cyg X-1 are 64 and 146, respectively. The chi-square values corresponding to a significance level of 0.5 for these degrees of freedom are 63.3 and 145.3, while the actual chi-square values of the long-term HR are 38.3 and 17808.6. Clearly, Cen X-3 is an source, while Cyg X-1 is an source. Using this method, we calculated the spectral and flux activity levels of bright sources in various energy band combinations. The number of sources for each activity level is shown in Table 3 .

Different activity levels of sources have different spatial distributions. Figure 14 [Figure 14: see original paper] shows the distribution of sources along Galactic longitude and latitude. Each subplot is divided into upper and lower parts: the upper part shows the overall distribution of all sources, while the shaded area in the lower part highlights the concentration range containing 68% of the total for each activity level (marked with upper and lower indices). The width represents the span in Galactic longitude or latitude, and the height corresponds to the number of sources, with specific values marked in the blank areas of the figure. It can be seen that sources with different activity levels show different clustering trends. sources are mainly concentrated in the range of , sources are concentrated in the region of , while the distribution of sources is more dispersed.

4.4 Overall Distribution Characteristics of HR for Binary Systems

During the Insight-HXMT Galactic plane scanning survey, the bright sources monitored are primarily X-ray binary (XRB) systems. Therefore, we first analyzed the overall characteristics of HR for XRBs. In XRBs, they can be more finely classified into many subclasses based on the mass and evolutionary stage of the primary or companion star. In this section, we first study the overall characteristics of HR for LMXBs and HMXBs. We fixed the low energy band at 2-4 keV and then selected 4-6, 5-7, 7-40, and 25-100 keV as high energy bands, calculating the HR for these combinations of high and low energy bands and using the median HR to characterize the overall trend. As shown in Table 3 , the fluxes of most binary systems are active.

Figure 15 [Figure 15: see original paper] shows the relationship between HR and number of sources, where subplots (a)-(d) represent all sources, sources, sources, and sources, respectively. The low energy band is fixed at 2–4 keV, with each color corresponding to different high energy bands (as shown in the legend). The vertical dashed lines indicate the median positions. By comparing the positions of the vertical dashed lines representing the medians, it can be seen that in each subplot, the HR distribution of HMXBs is shifted to the right compared to LMXBs, meaning that the spectra of HMXBs are harder than those of LMXBs. Combining the information in Figure 15, we can see that:

1. In these combinations of high and low energy bands, the overall HR of HMXBs is always higher than that of LMXBs. This trend is observed in all sources, sources, and sources. Since the number of flux-stable XRBs is relatively small, with some energy bands having none or only one, they are difficult to include in the comparison.
2. In LMXBs, the spectra of sources are generally harder than those of sources, while in HMXBs this trend is opposite below 7 keV. The overall HR of HMXBs is higher than that of LMXBs, meaning HMXB spectra are harder, which is consistent with the conclusion of Fabbiano [19]. We believe this is related to the modulation effect of different magnetic field strengths on accreted material:
    - In accreting neutron star systems, HMXBs are generally younger than LMXBs. Their relatively short accretion times allow them to retain more primordial magnetic fields, so the surface magnetic field strength of NS-HMXBs is generally higher than that of LMXBs.
    - In strong magnetic field environments, charged particles accreted from the companion star experience very strong modulation and are dragged to the magnetic poles of the primary star to form accretion columns. These columns contain extreme environments with high temperature, high pressure, and strong magnetic fields, where a series of thermal and non-thermal radiation processes occur.
    - In weak magnetic field accreting binary systems, the modulation effect of the magnetic field decreases, making it difficult to support the formation of accretion columns at the magnetic poles. In this case,

the accreted material is pulled into a circular orbit, forming a Keplerian disk, and the resulting X-ray radiation is mainly composed of thermal radiation from the accretion disk and the neutron star surface [20].

In summary, in accreting neutron star systems, the spectra of HMXBs are generally harder than those of LMXBs. It should be noted that some of the LMXBs and HMXBs are also BHB systems, but since BHBs account for a small proportion in binary systems [21], they have little impact on the overall distribution trend, so we ignore them here.

4.5 HR Distribution of Different Types of Bright Sources in 2-7 keV

Among the bright sources detected in 2-7 keV, in addition to many known types of sources, there are many currently unclassified sources. We analyzed the distribution of hardness ratios HR1 (5-7 keV/3-5 keV) and HR2 (4-6 keV/2-4 keV) for bright sources. In addition to studying the HR characteristics of known types of sources, we also attempted to explore the possible types of unclassified sources from these distributions. There are 142 bright sources in the target energy band, of which 7 types have too small sample sizes to be included in the statistical analysis, so we removed them. These 7 types are: cataclysmic variables (IGR J18308-1232, SS Cyg), Seyfert 2 galaxy (IGR J16024-6107), radio source (AX J1841.3-0455), binary or multiple star system (AX J1847.6-0156), galaxy cluster (Oph Cluster), and Be star (gam Cas). The remaining 135 sources, excluding unclassified sources, include the following types: HMXB, LMXB, SNR, Pulsar, and Seyfert 1 galaxy. Figures 16 [Figure 16: see original paper] and 17 [Figure 17: see original paper] show the distribution of HR1 and HR2 for these sources, with different colors representing different types of sources.

In Figure 17 [Figure 17: see original paper], each subplot represents one type of source, and the dashed lines indicate the positions of median HR ( ), with specific values also shown in the blank areas of each subplot. By using medians to characterize overall trends, we find that HMXBs have the largest HR1 and HR2 among these types. We calculated the correlation between HR1 and HR2 for different types of sources, with results of 0.62 (LMXB), 0.93 (HMXB), 0.66 (Pulsar), 0.69 (SNR), 0.48 (Seyfert 1), and 0.59 (unclassified). This suggests that the correlation between HR1 and HR2 may differ for different types of sources. It should be noted that the correlation coefficient does not have much physical meaning here, but it can be used to roughly estimate which type of source unclassified sources are more similar to. Through the correlation coefficients and histograms, we can find:

1. The HR1 of LMXBs is relatively uniformly distributed in the range of 0.2 to 0.6, while HR2 shows a trend of concentrating around 0.4.
2. HMXBs have the widest HR distribution among these types and the hardest overall spectra.

3. The HR distribution range of unclassified sources is relatively close to that of LMXBs, and their correlation coefficient is closest to that of LMXBs. The overall distribution trend also shows a movement from relatively uniform to clustering around a certain value. Therefore, based solely on the distribution, it can be speculated that LMXBs may account for a larger proportion among unclassified sources.

Figures 18 [Figure 18: see original paper] and 19 [Figure 19: see original paper] show the distribution of HR1 and HR2 for binary systems. In these binary systems, most primary stars have clear classifications, but some have unclear classifications (marked as '?' in the figures). From the HR distribution of binary systems with known primary star types, we can see that the HR of NS-HMXBs is significantly higher than that of NS-LMXBs, and the HR of NS-LMXBs is higher than that of all BHBs. In BHBs, the primary star is believed to have no solid surface [22], so in its quiescent state, radiation is dominated by thermal components from the disk, making its spectrum softer than that of NSBs. When it enters the outburst state, it exhibits rich spectral variation processes. At this time, when non-thermal radiation from regions such as jets and coronae dominates, the spectrum can become very hard. BHBs spend a relatively small proportion of time in outburst states, thus showing relatively soft spectral characteristics overall. Additionally, we can use Figures 18–19 to speculate on the possible types of several XRBs with unclear primary star types. First, the HR positions of 'LMXB/?' are at the peak of the NS-LMXB distribution, larger than the median HR of BH-LMXB. Second, the HR of 'HMXB/?' is significantly higher than that of BH-HMXB, while in Figure 19 [Figure 19: see original paper] (b) some 'HMXB/?' have HR near BH-HMXB. Therefore, it can be speculated that the source with unclear primary star type in LMXBs is more likely to be NS-LMXB, while in HMXBs, although some sources may be BH systems cannot be ruled out, NS-HMXB may account for a larger proportion.

4.6 HR of Transient XRBs Between Low-Flux and Outburst States

We analyzed the HR of seven transient sources that showed violent outbursts during the first four years of monitoring, comparing their differences between outburst and low-flux states. Here, a source is considered to have entered the outburst state when the 3-σ lower limit of the flux in a single scan is higher than the detector sensitivity; otherwise, it is considered to be in a low-flux state. Table 4 provides basic information for these seven sources (serial number, name, position, type, average HR in outburst state, and average HR in low-flux state).

Figure 20 [Figure 20: see original paper] shows the distribution of average HR in these two states, where the dashed line in the middle represents the condition where the average hardness ratio in the low-flux state equals that during outburst. The error bars for each data point represent the errors of the average HR in the two states. Since the flux is relatively low in the low-flux state, the corresponding HR errors are larger. From Table 4 and Figure 20, we can see that:

1. The three black hole binary systems GX 339-4, MAXI J1820+070, and MAXI J1348-630 have larger lower limits of average HR in the low-flux state than in the outburst state. This is consistent with the q-shaped trajectory commonly used to describe state transitions of BHBs in HID diagrams.
2. In both low-flux and outburst states, the HR of the two NS-HMXBs SWIFT J0243.6+6124 and 1A 0535+262 is higher than the remaining five binary systems, further confirming the conclusion in the previous subsection.

5 Summary

As China' s first general-purpose space X-ray telescope, Insight-HXMT has been operating smoothly in orbit for over eight years. The Galactic plane scanning survey, as one of its three core missions, occupies one-quarter to one-third of the observation time. It has achieved cumulative sensitivities of , , and in 2-6 keV (LE), 7-40 keV (ME), and 25-100 keV (HE), respectively. Insight-HXMT conducted long-term flux monitoring for more than 1300 known X-ray sources on the Galactic plane, detecting X-ray signals from more than 200 celestial bodies and constructing a wide-band monitoring source catalog.

Based on the analysis of these bright sources, we studied their flux variations. By investigating the relationship between and source type, we found that:

1. The fluxes of most supernova remnants are stable. The flux variations of most isolated pulsars and Seyfert 1 galaxies are very small or nearly stable.
2. The flux of HMXBs is more active than that of LMXBs in any energy band. In 2-6 keV and 7-40 keV, the flux variation of BHBs is greater than that of NSBs.
3. Most NS-LMXBs show smaller flux variation amplitudes in 2-6 keV than in higher energy bands, which may be related to the spectral components of NS-LMXBs.
4. The of HMXBs shows more complex variations across different energy bands, which may be related to more diverse accretion processes in different types of HMXBs.

By classifying all bright sources into three major categories (, , and sources) based on their flux and spectral activity, we analyzed the HR distribution characteristics of these three groups. Through comparing the HR distribution characteristics below 7 keV for different types of sources, we found that LMXBs may account for a larger proportion among unclassified sources, while NSXBs may account for more in binary systems with unclear primary star types. In studying the spatial distribution characteristics of the three activity groups, we found obvious clustering trends: sources are mainly concentrated in the range of , sources are concentrated in the region of , which is a phenomenon worth noting.

In the future, as more domestic and international space X-ray telescopes are put into operation, the scanning observations of Insight-HXMT will also be adaptively adjusted. It is planned to conduct joint Galactic plane scanning observations with the EP (Einstein Probe) satellite to fully leverage the advantages of both. With its advantages of wide detection energy band, high energy resolution, and high time resolution, Insight-HXMT can conduct in-depth spectral and timing studies of sources. The EP satellite has the largest instantaneous field of view (3600 deg^2) in the soft X-ray band and positioning accuracy better than arcminute for weak sources, showing significant advantages in detecting faint variable sources. Through joint scanning observations by Insight-HXMT and EP, complementary advantages can be achieved, and new results are expected in the field of unknown short-timescale variable sources.

Acknowledgments This work utilizes data from the Insight-HXMT mission, funded by the China National Space Administration (CNSA) and the Chinese Academy of Sciences (CAS).

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Note: Figure translations are in progress. See original paper for figures.