

## Advances in Insight-HXMT Observations of Isolated Pulsars and Accreting Millisecond Pulsars (Postprint)

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### Abstract

Insight-HXMT (Insight-Hard X-ray Modulation Telescope) is China's first space X-ray astronomical satellite, with primary scientific objectives to investigate compact objects such as black holes and neutron stars and monitor violent explosive phenomena including gamma-ray bursts; isolated X-ray pulsars and accreting millisecond X-ray pulsars also constitute important observational targets for Insight-HXMT. To date, Insight-HXMT has observed seven isolated pulsars and five accreting millisecond pulsars. First, we present the high-precision pulse profiles and phase-resolved spectra over a broader energy band obtained from Insight-HXMT observations of the Crab Nebula pulsar, and have derived the evolutionary characteristics of X-ray spectral properties and spectral parameters with phase; furthermore, we have investigated the delayed acceleration features during this pulsar's period glitch and whether the glitch induces variations in X-ray emission; additionally, orbit determination algorithms have been studied utilizing X-ray pulsars. Second, we describe the outbursts of five accreting millisecond pulsars observed by Insight-HXMT, during which hard X-ray pulsed radiation was detected, and report the discovery that MAXI J1816-195 exhibited spin-up, thereby constraining the stellar magnetic field.

### Full Text

### Preamble

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## Progress on Isolated Pulsars and Accreting Millisecond Pulsars Observed by Insight-HXMT

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### Abstract

The Insight-HXMT (Insight-Hard X-ray Modulation Telescope) is China's first space X-ray astronomical satellite. Its primary scientific objectives are to study compact objects such as black holes and neutron stars and to monitor violent eruptive phenomena like gamma-ray bursts. Isolated X-ray pulsars and accreting millisecond X-ray pulsars are also important observational targets for Insight-HXMT. To date, Insight-HXMT has observed seven isolated pulsars and five accreting millisecond pulsars. This paper first introduces the high-precision pulse profiles and broader energy band phase-resolved spectra obtained from Insight-HXMT observations of the Crab pulsar, revealing the evolution characteristics of X-ray spectral properties and spectral parameters as a function of phase. We further investigate the delayed spin-up characteristics during the pulsar's period glitches and whether these glitches cause changes in X-ray radiation, and we conduct research on orbit determination algorithms using X-ray pulsars. Second, we present the outbursts of five accreting millisecond pulsars observed by Insight-HXMT, during which hard X-ray pulsed radiation was detected. Notably, MAXI J1816-195 showed spin-up and provided constraints on the neutron star's magnetic field.

**Keywords** pulsars: isolated pulsar, pulsars: accreting millisecond pulsar, telescopes: Insight-HXMT

**Classification:** P142; **Document code:** A

### 1 Introduction

In October 1967, Antony Hewish and Jocelyn Bell discovered regular pulsed signals while examining radio signals from a radio telescope. The period was extremely stable at 1.337 s, and several similar pulsed signals were subsequently found in the recorded data [1]. In 1968, Gold and Pacini identified these objects as rotating strongly magnetized neutron stars [2-3]. Known as pulsars, these objects are considered one of the four major astronomical discoveries of the 1960s, alongside quasars, cosmic microwave background radiation, and interstellar organic molecules. Generally, neutron stars have a mass of about 1.4 solar masses, a radius of approximately 12 km, and core densities reaching several times nuclear density. Many extreme astrophysical phenomena may be associated with neutron stars, such as supernovae and gamma-ray bursts. From the perspective of stellar evolution, when intermediate-mass stars reach their late

evolutionary stages, core collapse leads to supernova explosions. The ejected material forms supernova remnants, leaving behind a rapidly rotating neutron star at the center [4]. With observational instruments covering wavelengths from infrared to gamma-ray, pulsars have exhibited diverse pulsed radiation phenomena. Currently, more than a few hundred pulsars have been detected with X-ray or gamma-ray pulsed radiation, while only a handful show optical emission. Here, high-energy pulsars are defined as sources exhibiting X-ray or gamma-ray pulsed radiation, meaning not only are the photon energies high, but the radiation mechanism also differs significantly from radio pulsars.

To date, the known pulsar catalog has included over 4000 sources (including discoveries from FAST [5-7]), each with distinct characteristics and belonging to various categories. Based on the energy source powering the radiation, pulsars can be classified into four types: (1) Rotation-powered pulsars, whose radiation energy is supplied by the star's rotational energy loss, such as the Crab pulsar and Vela pulsar; (2) Accretion-powered pulsars, which convert gravitational potential energy into electromagnetic radiation by accreting matter from a companion star, typical examples include high-mass X-ray binaries, low-mass X-ray binaries, and transients; (3) Magnetars, which are generally considered to be powered by magnetic field energy [8]; (4) X-ray dim isolated neutron stars, which can only radiate residual thermal energy after all possible energy sources have been exhausted [9].

Rapidly rotating pulsars are surrounded by a co-rotating magnetosphere filled with charged particles. These particles are accelerated by strong electric fields and produce high-energy radiation through physical processes such as curvature radiation, synchrotron radiation, and inverse Compton scattering, thereby emitting X-ray and gamma-ray photons. Pulsar radiation models aim to investigate issues related to particle production locations, acceleration processes, acceleration regions, and radiation mechanisms [10]. Currently, mainstream radiation models include the polar cap model [11], outer gap model [12-14], slot gap model [15], and annular gap model [16]. Although the locations of acceleration and radiation regions differ significantly among these models, they all lie within the light cylinder. In recent years, new magnetospheric models have been proposed, such as the FIDO (Force-free Inside and Dissipative Outside) model [17], various current sheet models [18], and kinetic/particle-in-cell simulations [19-20]. These new models and research results suggest that high-energy radiation is produced outside the light cylinder. While these classical dipole radiation models and the latest magnetospheric models can explain some current observational results, such as pulse profile shapes and phase-resolved spectra, no single model can apply to all cases [10]. Therefore, research on pulsar radiation region structure still requires new models that must be verified and constrained through observational results [10].

For rotation-powered pulsars, the spin period gradually increases, but there are also instances of instability where the spin period changes abruptly, known as period glitches [21-22]. Based on current observational samples, most glitches

manifest as sudden spin-ups, some as gradual spin-ups, and a few even as spin-downs. Detailed observations show that glitches are often followed by one or several exponential recovery components, providing an excellent opportunity to understand the internal structure of neutron stars. The current theoretical explanation posits that the neutron star's crust and magnetosphere are coupled. The magnetosphere's radiation carries away rotational energy, slowing down the crust. The superfluid beneath the crust is weakly coupled to the crust, so the neutron star's interior maintains a rapid rotation. As the crust continuously loses angular momentum, the rotational speed difference between the interior and exterior of the neutron star increases. When this difference reaches a critical value, the coupling between the interior fluid and the crust suddenly increases, rapidly transferring internal angular momentum to the crust [23].

Millisecond pulsars are an older class of pulsars with extremely fast rotation speeds. The fastest known pulsar has a period of 1.4 ms, and its period derivative is significantly lower than that of normal pulsars [24]. These millisecond pulsars are distributed not only in the Galactic disk but also in globular clusters; for example, PSR B1821–24 was the first isolated millisecond pulsar discovered in a globular cluster (M28) [25]. Millisecond pulsars exhibit X-ray and gamma-ray pulsed radiation. Additionally, there are accreting millisecond pulsars. Currently, it is generally believed that millisecond pulsars originate from the accretion-recycling of normal pulsars. The discovery of SAX J1808.4–3658, the first accreting millisecond pulsar, validated this hypothesis [26]; meanwhile, direct observations of transitions between accretion and pulsar phases in PSR J1023+0038 and IGR J18245–2452 have provided direct support for this view [27–28]. Furthermore, the Fermi telescope has discovered 127 gamma-ray millisecond pulsars [10]. Notably, pulsars have stable spin evolution, especially millisecond pulsars, a characteristic known as nature's most accurate clock, which can be applied to pulsar navigation, pulsar timing arrays, and low-frequency gravitational wave detection [29–30].

The radiation mechanism and internal structure of pulsars are two fundamental questions in pulsar research. Although pulsars exhibit rich observational phenomena across various wavelengths with numerous theoretical explanations, the origin of pulsar radiation and the specific conversion processes remain poorly understood, and the internal composition of neutron stars is even more mysterious. Using Insight-HXMT to observe the long-term evolution and short-timescale variations (such as glitches and state changes) of pulsars allows us to explore the origin of pulsar radiation, while using the evolutionary behavior during glitches to probe the secrets of pulsar internal structure. Meanwhile, accreting millisecond X-ray pulsars are also important observational targets for Insight-HXMT.

## 2 Insight-HXMT Observations

The “Insight” satellite, formally known as the Hard X-ray Modulation Telescope satellite, is China's first X-ray astronomical satellite, launched on June 15,

2017, from the Jiuquan Satellite Launch Center [31]. It operates in a near-Earth circular orbit at 550 km altitude, primarily used to observe and study black holes, neutron stars, and gamma-ray bursts. The satellite consists of the High Energy X-ray Telescope (HE, 20-250 keV, 5100 cm<sup>2</sup>) [32], the Medium Energy X-ray Telescope (ME, 8-35 keV, 952 cm<sup>2</sup>) [33], and the Low Energy X-ray Telescope (LE, 1-12 keV, 384 cm<sup>2</sup>) [34], achieving for the first time coverage of the 1-250 keV energy band, which facilitates the observation and study of X-ray celestial radiation mechanisms from different energy bands [32-35]. X-ray pulsars are also important observational targets for Insight-HXMT, which has currently observed seven isolated pulsars and five accreting millisecond X-ray pulsars. This paper briefly introduces the observational results of Insight-HXMT on isolated pulsars and accreting millisecond pulsars.

### 3.1 Spin Evolution and Glitches

The Crab pulsar was born from a bright supernova explosion in AD 1054 (SN1054) and was discovered in 1968 [36]. Pulsed radiation from the Crab pulsar has been observed from the lowest detectable radio band at 10 MHz up to TeV high-energy gamma rays, with its pulse profile showing a nearly double-peaked structure across all bands [37]. Additionally, the Crab pulsar serves as a powerful central engine, continuously injecting energy into the surrounding nebula and causing it to expand rapidly. Therefore, it is not only a famous celestial object observed by various astronomical facilities but also a source used by Insight-HXMT for instrument performance calibration [38]. A dedicated 12.5 m radio telescope at Jodrell Bank monitors this pulsar [39]. Previous observations indicated that large glitches in the Crab pulsar exhibit a delayed spin-up component with a characteristic timescale of about 1 day, which is highly significant for studying pulsar structure [40-41].

In November 2017, the Crab pulsar experienced the largest glitch in its observational history, which was observed in detail by Insight-HXMT, as shown in Figure 1 [Figure 1: see original paper]. Research shows that this glitch also had a delayed spin-up component with a characteristic timescale of 2 days (generally, glitch timescales are on the order of seconds, after which an exponential recovery process begins) [42]. In July 2019, the Crab pulsar experienced another glitch of similar magnitude, and timing results indicated that this glitch also contained a delayed spin-up component (as shown in Figure 2 [Figure 2: see original paper]) [43]. The glitches in 2004 and 2011 also had relatively large magnitudes. Using historical observational data for timing analysis, results show that these two glitches also contained delayed spin-up components, as shown in Figure 1. Considering four known glitch events, a total of six events show similar components. The presence of this component correlates with the glitch magnitude—that is, the larger the glitch magnitude, the longer the timescale of the delayed spin-up component. This correlation is shown in Figure 3 [Figure 3: see original paper]. Finally, as shown in Figure 4 [Figure 4: see original paper], statistical results indicate that samples with delayed spin-up components are also those

with relatively large glitch magnitudes [42].

Using detailed observations of the Crab pulsar's glitches by Insight-HXMT, we can quantitatively study the impact of glitches on X-ray pulsed radiation properties. As shown in Figure 5 [Figure 5: see original paper], the X-ray flux of the pulsar showed no change before and after the glitch, which is inconsistent with the change in spin-down energy (assuming the conversion efficiency from spin-down energy to X-ray pulsed radiation remains constant). At the current observational precision, this inconsistency suggests that the spin evolution behavior during this glitch was dominated by internal processes and did not affect the external pulsed radiation region. As shown in Figures 6 [Figure 6: see original paper] and 7 [Figure 7: see original paper], the absence of significant differences in X-ray pulse shapes before and after the glitch indicates that the X-ray pulse profiles did not change significantly during these two large glitches [43].

### 3.2 Evolution of Pulsar Braking Index

PSR B0540-69 is located in the Large Magellanic Cloud, with a characteristic age of about 1670 years and a pulse period of 50 ms, corresponding to a spin-down luminosity of  $10^{38}$  erg/s. These characteristics are very similar to those of the Crab pulsar, earning it the nickname "Crab pulsar's cousin or twin." In December 2011, the pulsar's spin-down rate suddenly increased by about 36% and remained stable, meaning the pulsar's spin-down energy loss rate suddenly increased by about 36% [44]. This change is referred to as a pulsar state change. As shown in Figure 8 [Figure 8: see original paper], after the state change, the pulsar's braking index became nearly zero. Further observations indicate that the braking index shows a rapid recovery trend, possibly implying that the pulsar's dipole magnetic field is gradually increasing [45].

### 3.3 X-ray Pulse Profiles and Phase-resolved Spectra

For the Crab pulsar, previous high-precision X-ray pulse profiles and phase-resolved spectra were limited to below 30 keV. Here, we performed joint phase-resolved spectral analysis across a broader energy band using the pulsar ephemerides from NICER (Neutron star Interior Composition Explorer), Insight-HXMT, and the Jodrell Bank radio telescope. Compared with previous broadband phase-resolved spectral analyses of the Crab pulsar, a broken power-law spectrum (bknpow) cannot adequately describe the spectral characteristics in the 2-250 keV broadband, particularly near the main and secondary peaks, requiring the introduction of a second break energy. When using a power-law model to fit the spectrum, the overall behavior of the spectral index is very similar across all phase intervals, with the index clearly increasing with energy—that is, the higher the energy, the larger the spectral index. Furthermore, we conducted quantitative analysis of pulse profiles in various energy bands. As energy increases, the separation between the double peaks

decreases; the full width at half maximum of both the main and secondary peaks increases; and the flux ratio between the double peaks increases [46-47]. Compared with the predictions of the “outer gap” model for the double-peak flux ratio and the bridge-to-main-peak flux ratio, the observational results show significant differences from the model predictions [48]. This poses new challenges for high-energy radiation models, while the trend of spectral index variation provides useful information for improving different models. To further investigate the relative positional relationship between the X-ray and radio pulse emission regions of the Crab pulsar, we used simultaneous observational data from Insight-HXMT and NICER to obtain more precise time delays, which can be fitted linearly with a slope of (as shown in Figure 9 [Figure 9: see original paper]) [49].

Insight-HXMT also conducted detailed pointed observations of the young pulsar PSR B1509-58, a typical soft gamma-ray pulsar [50]. Using observational data from Insight-HXMT and other telescopes, particularly from the high-energy telescope, Takata et al. systematically fitted the spectrum in the 0.5–200 keV band [51]. The fitting results show that the spectrum of PSR B1509-58 requires a broken power-law description, with a break energy at 5 keV. The phase-resolved spectrum can also be described by the same model, with the break energy also near 5 keV [51]. Further analysis indicates that the conversion efficiency of this class of soft gamma-ray pulsars is consistent with that of other gamma-ray pulsars, meaning the radiation characteristics of this class are primarily determined by the viewing angle [51].

### 3.4 Progress in Pulsar Navigation

Pulsar navigation is also one of the important research objectives of Insight-HXMT. The navigation principle is that the observed pulsar signal is modulated by the spacecraft’s motion—that is, the pulse arrival time depends on the spacecraft’s spatial position. Therefore, by analyzing the characteristics of the pulse signal received by the detector, the spacecraft’s position and velocity in space can be determined. Since pulsars are extremely distant from Earth and unaffected by human factors, their navigation accuracy does not change with the spacecraft’s location, making them ideal navigation beacons in deep space that have received considerable attention. The European Space Agency and NASA have successively released relevant research plans. NASA announced in 2018 that the SEXTANT (The Station Explorer for X-ray Timing and Navigation Technology) project on the International Space Station successfully conducted real-time orbital autonomous navigation experiments using pulsars [52]. After 7.5 hours of pulsar observations, the autonomous navigation accuracy reached 5 km [52]. Meanwhile, China has also conducted extensive theoretical and experimental research on pulsar navigation. For example, using observations of the Crab pulsar by the “Polarimeter for Gamma-ray bursts” (POLAR) on Tiangong-2, China completed its first space-based pulsar navigation experiment [53]; China also launched the X-ray Pulsar Navigation test satellite XPNAV-01

to conduct pulsar detection and related research [54]. As shown in Figure 10 [Figure 10: see original paper], using 5 days of observational data from the Crab pulsar and through the “pulse profile significance versus satellite orbit correlation analysis” algorithm, the results show that the satellite positioning accuracy reached 10 km, equivalent to 3.3 km, meaning that Insight-HXMT’s navigation experiment accuracy is comparable to that of NICER/SEXTANT [30].

## 4 Progress in Millisecond Pulsar Observations

Accreting Millisecond X-ray Pulsars (AMXPs) are a special class of low-mass X-ray binaries where the compact object is a rapidly spinning, recycled pulsar and the companion is a low-mass main-sequence star or white dwarf. In 1998, Wijnands and van der Klis discovered X-ray pulsations at approximately 401 Hz from SAX J1808.4-3658 [26]. Since the pulse frequency was modulated by the binary orbital motion, they successfully measured the binary orbital parameters, marking the first confirmed AMXP. With the operation of high-energy telescopes such as RXTE (The Rossi X-ray Timing Explorer), XMM-Newton (X-ray Multi-Mirror Mission), Chandra, INTEGRAL (The International Gamma-Ray Astrophysics Laboratory), Swift, MAXI (Monitor of All-sky X-ray Image), and NICER, all-sky monitoring of X-ray source outbursts has been achieved. To date, 23 AMXPs have been discovered and identified, and this number continues to grow [55-56]. These AMXPs were all detected by X-ray telescopes during outbursts, and through timing analysis, their orbital periods were measured to range between 40 minutes and 9 hours, with spin periods between 1.9 and 10 ms. The outburst of IGR J1900.1-2455 lasted for more than ten years, making it the longest-lasting AMXP observed to date. The recurrence times of AMXP outbursts are difficult to predict; most sources have only been observed to outburst once, implying recurrence periods of at least ten years. So far, five AMXPs have shown repeated outbursts, with the shortest recurrence time for NGC 6440 X-2 being about one month, while SAX J1808.4-3658 has been observed to outburst eight times since its discovery, with an average recurrence interval of 2-4 years [55]. Studies have also found that the broadband X-ray pulse profiles during AMXP outbursts are closely related to key parameters such as binary orbital inclination, magnetic inclination, accretion column height, and neutron star mass and radius [57].

The magnetic field decay timescale for an isolated accreting neutron star is extremely long (over  $10^7$  years), making direct observation of its magnetic field evolution difficult. However, through multi-wavelength observations of large neutron star samples, the magnetic field distributions of different subclasses (such as normal pulsars versus millisecond pulsars) can be studied to infer their overall evolutionary patterns. For AMXPs during outburst, the magnetic field strength can be calculated based on accretion torque theory. For example, Mukherjee et al. (2015) used observed luminosity extrema to calculate the magnetic field range for 14 AMXPs [58]; Sanna et al., while studying the evolution of X-ray pulse profiles of IGR J17591-2342, found that the source spun down

during outburst. Combining accretion torque theory and correcting for accretion rate, they calculated its magnetic field strength to be approximately  $10^8$  Gs [59]. For quiescent AMXPs, the dipole magnetic field strength can be estimated from the star's luminosity and spin-down rate [60–61], or based on standard accretion disk theory and optical observations during quiescence [26, 62–64]. For AMXPs with multiple outbursts, the magnetic field can also be calculated from the spin-down between outbursts due to magnetic dipole radiation. Hartman et al. (2011) used this method to calculate the magnetic field of IGR J00291+5934 as  $10^8$  Gs [65]; Sanna et al. (2018) similarly obtained a magnetic field range of  $10^8$ – $10^9$  Gs for Swift J1756.9–2508 [66]. In summary, the calculation of AMXP magnetic field strength primarily depends on the star's spin frequency, frequency derivative, and luminosity, while also being affected by uncertainties in parameters such as distance, mass, and radius.

Current observations show that AMXPs are mostly classified as atoll sources among X-ray transients, with typical X-ray luminosities of  $10^{36}$ – $10^{37}$  erg/s during outburst. Outburst durations generally range from days to months, with typical rise timescales of 2–3 days, gradually decaying to quiescence after reaching peak. AMXP outburst recurrence times are unpredictable, with most sources observed to outburst only once, implying recurrence periods of at least ten years. To date, five AMXPs have shown repeated outbursts, with NGC 6440 X-2 having the shortest recurrence time of about one month, while SAX J1808.4–3658 has been observed to outburst eight times since discovery, with an average recurrence interval of 2–4 years [55]. Studies have found that broadband X-ray pulse profiles during AMXP outbursts are closely related to key parameters including binary orbital inclination, magnetic inclination, accretion column height, and neutron star mass and radius [57].

The transition of AMXPs from accretion state to radio emission state is an important prediction of the pulsar “recycling mechanism.” AMXP IGR J18245–2452 was detected with radio pulsed radiation two weeks after entering quiescence, confirming its transition from accretion phase to pulsar phase on a short timescale, making it the only state-transitional millisecond pulsar observed to date [67]. Previously, Iacolina et al. searched for radio pulses from multiple sources including XTE J0929–314 and XTE J1751–305 in quiescence, but without success [68–69]. This indicates that whether radio pulsed radiation from neutron stars can be observed in the quiescent state of LMXBs depends on various factors, including whether the radio beam points toward the observer, telescope sensitivity, source distance, and free-free absorption by circumstellar medium. In the gamma-ray band, Fermi/LAT discovered that radio millisecond pulsars generally exhibit high-energy pulsed radiation powered by a small fraction of the pulsar's spin-down energy loss [70], while AMXP gamma-ray pulsed radiation is not affected by free-free absorption from the medium. Therefore, searching for gamma-ray pulsed radiation can be used to determine whether AMXPs have undergone state transitions, but no gamma-ray pulsed radiation signals from AMXPs have been detected to date [71–72]. In the future, with precise measurements of AMXP orbital parameters and accumulated gamma-

ray observational data, it is hoped that their gamma-ray pulsed radiation will eventually be detected.

Since its operation, Insight-HXMT has observed five AMXPs: Swift J1756.9-2508, MAXI J1816-195, SAX J1808.4-3658, IGR J17498-2921, and SRGA J144459.2-604207. Swift J1756.9-2508 was discovered by Swift/BAT during its 2007 outburst, and coherent X-ray pulsations at 182 Hz confirmed the compact object as an AMXP. In subsequent Swift and RXTE observations, its orbital period was measured to be 54.7 minutes, and based on its mass function, the companion was found to be a highly evolved white dwarf with a mass between 0.0067-0.03 solar masses. Swift J1756.9-2508 experienced three additional outbursts in 2009, 2018, and 2019. During the 2018 outburst, Insight-HXMT observed this source for 20 ks, achieving a signal-to-noise ratio of about 5 in the 5-45 keV pulse profile, as shown in Figure 11 [Figure 11: see original paper], and the pulse profile shape was consistent with results from other telescopes, indicating that Insight-HXMT's timing measurements for rapidly spinning pulsars are very accurate. Observations show that the pulsed fraction increases from 4% to 7.5% in the 1-5 keV band and saturates at higher energies. Additionally, no significant change in spin frequency was found in the data. By comparing the observed time of ascending node with predicted values, we found no significant evolution in the binary system's orbital period since the first outburst in 2007.

On June 7, 2022, the MAXI gas slit camera detected an X-ray outburst from the new transient source MAXI J1816-195 [74]. Follow-up observations by NICER detected pulsed radiation and Type I X-ray bursts from this source, confirming it as an AMXP with a spin frequency of 528 Hz, an orbital period of 4.83 hours, and a projected semi-major axis of 0.26 light-seconds [75-78], with a companion mass between 0.10-0.55 solar masses [75]. Meanwhile, Insight-HXMT detected X-ray pulsations from MAXI J1816-195 in the hard X-ray/soft gamma-ray band [79]. Bult et al. proposed a flux bias model that considers accretion torque at the neutron star surface and/or hot spot wandering to explain the timing residuals throughout the outburst [75]. Chen et al. reported that Insight-HXMT detected 73 Type I X-ray bursts from MAXI J1816-195, obtaining an upper distance limit of 6.3 kpc [80]. Using data from Insight-HXMT's medium and high-energy telescopes, NICER, and NuSTAR, we systematically studied the X-ray timing and spectral behavior of MAXI J1816-195 during its 2022 outburst, covering 0.8-210 keV. First, we used Insight-HXMT-HE data for timing analysis throughout the outburst, finding that the residual behavior was complex and confirmed by Insight-HXMT-ME and NICER observations, particularly during the rising and final phases of the outburst. Therefore, we divided the entire outburst into a (noisier) rising phase from MJD 59737.0 to 59741.9, lasting about 5 days, and a decay phase from MJD 59741.9 to 59760.6, lasting 19 days. The timing of the decay phase could be fitted with a timing model including frequency and frequency derivative, with a value indicating the pulsar was in a spin-up state. We found that the model proposed by Bult et al. could not fully explain our observational data [75]. Furthermore, we observed hard X-ray pulsed radiation up to 95-210 keV in Insight-HXMT-HE data, with the pulse

profile remaining significant in the 95-210 keV band, as shown in Figure 12 [Figure 12: see original paper]. Such high-energy pulsed radiation suggests a non-thermal origin. Finally, the pulse profile remained quite stable throughout the outburst, could be well described by a truncated Fourier series with two harmonics (fundamental and harmonic), and these two components were consistent across the 0.8-64 keV range. Based on these observations, we also estimated the magnetic field range of MAXI J1816-195 to be  $10^8$ - $10^9$  Gs, consistent with most other AMXPs. Additionally, during the 2023 outburst of IGR J17498-2921, Insight-HXMT, together with NICER and other telescopes, observed the source and detected significant pulse signals across a broad 0.5-150 keV band, with the pulsed fraction increasing from about 2% at 1 keV to about 13% at 66 keV [81].

Furthermore, Insight-HXMT has detected pulsed radiation from SAX J1808.4-3658 and SRGA J144459.2-604207, with related results to be published in subsequent papers.

## 5 Summary and Outlook

Insight-HXMT has accumulated rich observational data on pulsars, requiring further mining of existing data. For accreting millisecond X-ray pulsars, higher-energy pulsed signals provide important constraints on the radiation region of accreting pulsars. Additionally, Insight-HXMT's high-energy telescope CsI detectors cover the MeV energy band, possessing the potential capability to observe MeV radiation from pulsars. Using this observational data to study the MeV radiation characteristics of pulsars will further reveal the geometric structure of high-energy radiation regions. China's Einstein Probe satellite and the China-France cooperative SVOM satellite have also been launched, which will expand X-ray observational capabilities. Joint observations with Insight-HXMT and these two X-ray telescopes will further enhance pulsar observational capabilities and open new discovery space.

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