Postprint: Cyclotron Absorption Lines and Accretion Physics of Accreting Pulsars in the HXMT Era

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Abstract

Since its launch in 2017, the Insight Hard X-ray Modulation Telescope (Insight-HXMT), leveraging its advantages of a broad energy band, large effective area, and high observation frequency, has become one of the most important astronomical satellites in the field of accreting X-ray pulsar research. It has made significant progress in the study of cyclotron absorption lines and accretion physics, mainly including detecting high-energy cyclotron absorption lines, revealing the evolution of cyclotron line energies, and observing radiation pressure-dominated accretion disks.

Full Text

Preamble

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Insight-HXMT Studies of Cyclotron Resonant Scattering Features and Accretion Physics in Accreting X-ray Pulsars

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Abstract

Since its launch in 2017, the Insight Hard X-ray Modulation Telescope (Insight-HXMT) has become one of the most important astronomical satellites for studying accreting X-ray pulsars, thanks to its wide energy band, large effective area, and high observational cadence. It has achieved significant progress in cyclotron absorption line and accretion physics research, primarily including the detection of high-energy cyclotron absorption lines, revealing the evolution of cyclotron line energies, and observing radiation-pressure-dominated accretion disks.

Keywords: stars: neutron, accretion, X-rays: binaries, pulsars: general

1 Introduction

X-ray accreting pulsars are magnetized neutron stars that appear in X-ray binary systems, typically with massive main-sequence companion stars. These objects possess extremely strong magnetic fields, reaching up to 10^{12}-10^{13} G, far exceeding anything achievable in Earth-based laboratories, making them natural laboratories for studying physics in ultra-strong magnetic fields. Observational studies of accreting pulsars have continued for nearly 50 years since the 1970s, accumulating a vast amount of data. Based on the nature of their companion stars, accreting pulsar systems can be broadly classified as either persistent sources or transients, with transients comprising the majority. Their luminosities span multiple orders of magnitude, from approximately 10^{34} erg/s to 10^{39} erg/s. At low accretion rates, systems may enter a "propeller" state where accretion near the magnetosphere ceases due to centrifugal forces, while at high accretion rates they can evolve into ultraluminous X-ray sources (ULXs). The strong magnetic field truncates the accretion flow at the magnetospheric radius, inside which matter falls along the pulsar' s dipole magnetic field lines onto the polar caps, where gravitational potential energy is converted into X-ray radiation that we observe. Because the magnetic axis is typically misaligned with the rotation axis, we observe periodically modulated X-ray flux. Interested readers are referred to the review article [**?**].

The energy spectra of accreting pulsars are dominated by non-thermal radiation, which can generally be described by phenomenological models such as a power law with a high-energy exponential cutoff (for possible mathematical forms, see review [**?**]). The spectra also exhibit narrow line features, including the Fe fluorescence line near 6.4 keV and cyclotron resonant scattering features (CRSF). The latter, commonly called "cyclotron lines," arise from the quantization of electron energy perpendicular to the magnetic field direction (Landau levels) in strong magnetic fields, appearing as broad absorption structures in the spectrum. The importance of cyclotron absorption lines lies in the fact that their central energy depends only on the local magnetic field strength: $E_{\mathrm{cyc}} \approx 11.6 \times B_{12}/(1+z)$ keV, where n is the quantum number, z is the gravitational redshift, and B_{12} is the magnetic field in units of 10^{12} G. Thus, cyclotron lines provide the most direct means of measuring magnetic fields in neutron star emission regions. Cyclotron lines are often not constant but vary with the source' s luminosity, spin phase, orbital phase, superorbital phase, and different stages of outbursts. It is important to emphasize that these variations in cyclotron line energy do not reflect changes in the neutron star' s intrinsic magnetic field, but rather result from changes in the radiation structure or direction in the polar cap region.

Therefore, studies of cyclotron lines, along with related timing and continuum spectral analyses, constitute the primary tools for investigating accretion and radiative transfer processes in polar cap regions.

In-depth studies of accreting pulsars require observational facilities with wide energy coverage and large effective areas. Important previous missions include BeppoSAX (Satellite per Astronomia a raggi X), RXTE (Rossi X-ray Timing Explorer), NuSTAR (Nuclear Spectroscopic Telescope Array), and INTEGRAL (International Gamma-Ray Astrophysics Laboratory). In 2017, the Chinese-led Insight Hard X-ray Modulation Telescope (Insight-HXMT) was successfully launched, featuring a wide energy band (1–250 keV) and a large effective area in the hard X-ray band (see [?] for details). Crucially, the satellite employs a flexible observation strategy that concentrates exposure time on bright outburst states, obtaining unprecedented high-quality data for important bursting sources such as Swift J0243.6+6124 and 1A 0535+262, making it one of the most important observatories in this research field. To date, researchers have published 36 papers on timing, spectral analysis, and theoretical modeling of accreting pulsars based on HXMT data covering 13 different sources. Due to space limitations, this review cannot cover all these studies comprehensively and therefore focuses on representative highlights.

2 A New Record for the Highest-Energy Cyclotron Absorption Line

Cyclotron lines typically have broad spectral features that can couple with the continuum, requiring wide energy coverage for their measurement. The HXMT satellite has detected cyclotron absorption lines in Her X-1, Vela X-1, Cen X-3, GRO J1008–57, Swift J0243.6+6124, and 1A 0535+262 [?, ?, ?, ?, ?, ?, ?], demonstrating its powerful detection capability, particularly at high energies. For example, in GRO J1008–57, the detection significance of the 90 keV cyclotron line was dramatically improved from the previous 2σ to 20σ [?]. During the peak of the outburst from the first Galactic ultraluminous X-ray source Swift J0243.6+6124, Kong et al. [?] discovered a cyclotron absorption line at 120–146 keV through phase-resolved spectroscopy. The broad-band spectrum and spectral fitting residuals for Swift J0243.6+6124 are shown in Figure 1 [Figure 1: see original paper]. This represents a new record for the highest-energy cyclotron line and marks the first measurement of a cyclotron line in an ultraluminous X-ray source. From this, the neutron star' s surface magnetic field can be inferred to be approximately 1.6×10^{13} G, which is significantly larger than previous estimates based on the "propeller" effect and accretion disk-flow interactions [?, ?]. This suggests the presence of a multipole magnetic field component, a theoretical prediction that has now been observationally confirmed for the first time through cyclotron line measurements in Swift J0243.6+6124. This result also has important implications for understanding the relationship between normal X-ray pulsars and ULXs, indicating that some ULXs have radiation mechanisms similar to ordinary X-ray pulsars, with fan-beaming emission patterns, and that their high estimated luminosities are intrinsic rather than due to strong radiation beaming [?, ?, ?]. On the other hand, based on spin evolution at low luminosities, Liu et al. [?] observed that the properties of the accretion flow may differ between different outburst states (strong and weak outbursts). At low luminosities, the pulsar may not always enter the "propeller" state, which challenges the use of the "propeller" effect to constrain the neutron star' s dipole magnetic field.

3 Evolution of Cyclotron Line Energy

The energy of cyclotron absorption lines typically varies with changes in the accretion structure at the polar caps. For example, in the well-observed source Her X-1, a positive correlation between cyclotron line energy and luminosity has been found, along with long-term evolution on timescales of decades [?, ?, ?, ?]. Since its launch, HXMT has observed Her X-1 multiple times, confirming this long-term evolutionary trend [?, ?], and will continue long-term monitoring to capture any sudden changes in cyclotron line energy as they occur.

In many sources, a correlation exists between cyclotron line energy and pulsar luminosity: most show a positive correlation, while only a few exhibit an inverse correlation at high luminosities [?, ?]. Theoretical models suggest that when the accretion rate is high (the supercritical accretion state; the opposite is subcritical), the high luminosity in the polar cap region creates strong radiation pressure that impedes the infall of accreting matter. This leads to the formation of an accretion column whose height increases with accretion rate. The luminosity at which the column just forms is called the critical luminosity [?, ?, ?, ?]. When the luminosity exceeds this critical value, the main emission region moves slightly away from the polar cap [?, ?], causing the local magnetic field strength to decrease and resulting in an inverse luminosity-cyclotron energy relationship. This inverse correlation had previously been observed only in V0332+53 [?, ?]. At the end of 2020, HXMT observations of the outburst state in 1A 0535+262 broke this solitary case. In this source, the cyclotron line energy was positively correlated with luminosity at low luminosities but inversely correlated at high luminosities [?], providing strong support for the theoretical model. Figure 2 [Figure 2: see original paper] shows the relationship between cyclotron absorption line energy and luminosity at different outburst stages. Subsequently, using pulse-to-pulse techniques, Shui et al. [?] conducted a more detailed analysis of the luminosity-cyclotron energy relationship, particularly extending it to lower luminosity ranges, providing observational guidance for theoretical modeling.

Another interesting issue is that, as shown in Figure 2, the evolution of cyclotron line energy differs between the rising and fading phases of outbursts. Moreover, studies of pulse profiles reveal that even at the same luminosity, the pulse profiles in the rising and fading phases show significant differences [?, ?]. This indicates that accretion rate is not the only factor affecting the accretion structure in the polar cap region, and further investigation of the details is needed.

4 Radiation-Pressure-Dominated Accretion Disks

Although the radiation we observe originates directly from the polar cap region near the neutron star, the properties of the accretion flow on larger scales (outside the magnetosphere) also significantly affect the timing and spectral characteristics of accreting pulsars. This occurs for two main reasons: (1) the geometric scale of the polar cap region is generally thought to be related to the thickness of the accretion disk, so changes in disk thickness affect the local accretion rate at the polar caps; and (2) variability in the accretion flow propagates to the polar cap region, causing non-periodic variations in flux that are primarily reflected in the power spectrum [?]. The classic Shakura-Sunyaev accretion disk theory posits that at low accretion rates, the disk is geometrically thin and optically thick, with pressure dominated by gas pressure, while at high accretion rates, radiation pressure gradually becomes dominant, affecting the vertical structure of the disk and creating a radiation-pressure-dominated thick disk [?]. However, this picture had never been observationally confirmed in accreting pulsars until now.

Doroshenko et al. [?] conducted a detailed study of the evolution of pulse profiles and power spectra in Swift J0243.6+6124; the long-term outburst evolution and accompanying timing changes are shown in Figure 3 [Figure 3: see original paper]. They found that the morphology of the pulse profiles underwent two abrupt changes with luminosity evolution. One can be explained by the formation of an accretion column, while the other likely results from the transition of the accretion disk from a gas-pressure-dominated thin disk to a radiation-pressure-dominated thick disk, the latter accompanied by a significant change in power spectrum morphology. Kong et al. [?] analyzed the spectral evolution of simultaneous data and found clear spectral changes near the luminosity where the pulse profile transitions occurred, supporting the physical picture of a radiation-pressure-dominated accretion disk at high luminosities. Wang et al. [?] and Liu et al. [?, ?] performed detailed analyses of Swift J0243.6+6124 using pulse fraction and torque models, with results at high luminosities also consistent with the radiation-pressure-dominated disk model. Another interesting phenomenon is that Liu et al. [?] found that at even higher luminosities ($> 10^{39}$ erg/s), the "luminosity-frequency derivative" relation deviates from the predictions of the radiation-pressure-dominated disk model. This may be because radiation from the accretion column irradiates the disk, driving a disk wind that removes some angular momentum. Additionally, based on pulse profile and power spectrum evolution, radiation-pressure-dominated accretion disks have been observed in other sources [?, ?], though the specific details differ noticeably between sources and require further observational study.

5 Summary and Outlook

Over the past seven years, by fully leveraging its advantages of wide energy coverage, high statistics, and high observational cadence, Insight-HXMT has become one of the most important satellites for research on accreting pulsars and has yielded fruitful results. In particular, its unprecedented high-quality observations of bright outburst states in transient sources have directly tested and advanced the development of physical models for polar cap accretion. In the future, HXMT will continue its previous observation strategy, aiming to achieve new breakthroughs in the following areas: (1) analyzing existing data using pulse-to-pulse techniques or capturing new outburst data to search for evidence of cyclotron lines at even higher energies; (2) continuing long-term monitoring of cyclotron line evolution in persistent sources such as Her X-1; (3) expanding the sample of sources for the luminosity-cyclotron energy relationship to confirm previously observed anomalous cases [**?**]; and (4) combining timing and spectral evolution to search for observational evidence of radiation-pressure-dominated accretion disks in more sources.

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