X-ray Polarimetric Imaging of Supernova Remnants and Pulsar Wind Nebulae (Postprint)

Authors: Tianxian Luo, Zhou Ping

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Abstract

High-energy particles in young supernova remnants and pulsar wind nebulae can produce X-rays through synchrotron radiation. Polarization measurements of this radiation help reveal the nature of the magnetic field in particle acceleration regions, thereby facilitating studies of particle acceleration mechanisms. The first X-ray polarization imaging satellite was launched at the end of 2021, and has already revealed X-ray polarization images of several young supernova remnants and pulsar wind nebulae. Observations show that Cas A and Tycho's supernova remnant have relatively low polarization degrees, with average values of approximately 2.5% and 9%, respectively; whereas the Crab Nebula and Vela pulsar wind nebula have relatively high polarization degrees, with average values of approximately 20% and 45%, respectively. The results indicate that the magnetic fields in pulsar wind nebulae are relatively ordered, while the magnetic fields in the particle acceleration regions of the two young supernova remnants are highly turbulent, and the magnetic field structure near the shock front exhibits a radial distribution. In the future, as the use of IXPE becomes more widespread and more telescopes such as the enhanced X-ray Timing and Polarimetry detector (eXTP) under construction in our country are put into operation, the magnetic field configurations and particle acceleration models of the aforementioned two types of celestial objects will be further constrained.

Full Text

Preamble

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X-ray Polarization Imaging of Supernova Remnants and Pulsar Wind Nebulae

LUO Tian-xian[1;2], ZHOU Ping[1;2]
(1. School of Astronomy and Space Science, Nanjing University, Nanjing 210046, China;
2. Key Laboratory of Modern Astronomy and Astrophysics, Ministry of Education, Nanjing 210046, China)

Abstract

High-energy particles in young supernova remnants and pulsar wind nebulae can produce X-ray synchrotron radiation. Polarimetric measurements of this emission help reveal the magnetic field properties in particle acceleration regions, thereby advancing our understanding of acceleration mechanisms. The first X-ray polarization imaging satellite, launched in late 2021, has unveiled the X-ray polarization images of several young supernova remnants and pulsar wind nebulae. Observations show that Cas A and Tycho's supernova remnant exhibit low polarization degrees, averaging approximately 2.5% and 9% respectively, while the Crab Nebula and Vela pulsar wind nebula display higher polarization degrees, averaging about 20% and 45% respectively. These results indicate that pulsar wind nebulae possess relatively ordered magnetic fields, whereas the particle acceleration regions in the two young supernova remnants feature highly turbulent magnetic fields with radial field structures near the shocks. Future progress will come from expanded IXPE observations and additional telescopes such as China's planned enhanced X-ray Timing and Polarimetry (eXTP) mission, which will further constrain magnetic field configurations and particle acceleration models for these two classes of objects.

Keywords: supernova remnants; pulsar wind nebulae; polarization; X-ray astronomy; particle acceleration

1 Introduction

Polarization of electromagnetic radiation reveals the magnetic field configuration and radiative transfer properties within and near the emission source. The polarization degree is defined as the ratio of polarized intensity to total intensity. For linear polarization, the polarization direction indicates the orientation of the electric field vector, which is perpendicular to the magnetic field vector, while the polarization angle measures the direction relative to celestial north (positive east of north). Pulsar wind nebulae and supernova remnants typically emit synchrotron radiation, whose polarization direction relates to the projected magnetic field orientation on the sky. The polarization degree depends on the degree of magnetic order: more ordered fields yield higher polarization. Consequently, synchrotron polarization reflects both the geometric structure and turbulent nature of magnetic fields.

Compared to radio emission, X-ray synchrotron radiation originates from higher-energy particles (electrons or positrons). The characteristic energy loss timescale for an electron of energy E in a magnetic field B is given by [?, ?]:

$$\tau_{\text{loss}} = 6.35 \times 10^{-13} B^{-2} E^{-1}$$

where B is the magnetic induction in Tesla, E is the energy in Joules, and τ_{loss} is the energy loss time in seconds. This relationship shows that higher-energy particles have shorter lifetimes, and their radiation originates increasingly close to the acceleration region. Therefore, X-ray polarization can probe magnetic field properties in particle acceleration zones more directly, providing crucial insights into acceleration mechanisms.

The first potential detection of X-ray polarization from the Crab Nebula occurred in 1971 using an Aerobee-350 sounding rocket [?]. Subsequent observations with OSO-8's two X-ray polarimeters confirmed the Crab Nebula's X-ray polarization at $(16.1 \pm 1.4)\%$ [?]. Traditional X-ray polarimetry relied on Thomson scattering, Compton scattering, or Bragg crystal diffraction, exploiting their polarization dependence [?]. However, these methods suffered from poor sensitivity, yielding reliable results only for bright sources and proving inadequate for extended sources. Such sources often contain regions with diverse polarization properties, requiring spatially resolved measurements. Recent advances in X-ray polarization imaging technology have resolved this long-standing limitation.

The current leading X-ray polarization imaging technique employs gas pixel detectors (GPDs), which utilize the photoelectric effect in thin gas layers. The ejected photoelectron's direction aligns primarily with the incident photon's electric field vector. Fine-structured electrodes record the interaction tracks left by these photoelectrons, and since the initial track segment contains information about the ejection direction, the incident polarization can be reconstructed [?]. Compared to traditional methods, GPDs offer dramatically improved sensitivity, enabling detailed X-ray polarization measurements for thousands of Galactic and extragalactic sources [?].

This technological breakthrough spawned several X-ray polarimetry missions: the European Space Agency's X-ray Imaging Polarimetry Explorer (XIPE) [?], NASA's Imaging X-ray Polarimetry Explorer (IXPE) [?], and China's enhanced X-ray Timing and Polarimetry (eXTP) mission [?]. XIPE was not selected for final implementation [?], eXTP remains in development, and only IXPE is currently operational. Launched in December 2021, IXPE carries three GPDs and represents the first X-ray polarization imaging observatory.

IXPE consists of three identical X-ray telescopes, each comprising an X-ray mirror module and a detector unit positioned at the focal plane. The detector core is a polarization-sensitive GPD. Each unit provides an effective area of 166 cm^2 at 2.3 keV, performing polarimetric and spectroscopic observations in the

2–8 keV band. IXPE's angular resolution is 24 –30 with a field of view of 12.9 [?].

China's eXTP mission, led by the Institute of High Energy Physics of the Chinese Academy of Sciences in collaboration with over 100 research institutes from more than 20 countries including Italy and Germany, will carry four instruments covering 0.5–30 keV: the Spectroscopic Focusing Array (SFA), Polarimetry Focusing Array (PFA), Large Area Detector (LAD), and Wide Field Monitor (WFM). The PFA employs GPD technology with angular resolution better than 30 , operating in the 2–8 keV band [?]. eXTP is scheduled for launch around 2027 [?].

X-ray polarization imaging observations are crucial for studying high-energy extended sources such as supernova remnants and pulsar wind nebulae. Since 2022, IXPE has observed several such objects, yielding new insights into their magnetic fields. This paper reviews the scientific questions addressed by X-ray polarization imaging of these sources, presents IXPE's discoveries, and discusses future prospects.

2 Supernova Remnants

Supernova remnants form when supernova blast waves sweep through the interstellar medium. Most Galactic supernova remnants were discovered through radio emission from GeV-energy relativistic electrons' synchrotron radiation [?]. To identify radiation from higher-energy electrons, higher-frequency observations are required. In 1995, Koyama et al. [?] detected X-ray synchrotron radiation from SN 1006, providing direct evidence that supernova remnants can accelerate cosmic rays to TeV energies and beyond. Since then, non-thermal X-ray emission from filamentary structures has been found in several young remnants, including Cas A, Tycho's supernova remnant, and G347.3–0.5 [?]. Diffusive shock acceleration is widely accepted as the particle acceleration mechanism in supernova remnants [?], but accelerating cosmic rays to the knee of the cosmic-ray spectrum requires magnetic field amplification, possibly through highly turbulent fields [?]. Since X-ray synchrotron radiation in young remnants originates from very-high-energy particle acceleration zones, X-ray polarimetry provides a vital probe of magnetic field geometry and turbulence near active acceleration sites.

2.1 Cas A

Cas A is a core-collapse supernova remnant approximately 340 years old with a diameter of 5.5 . Its X-ray synchrotron-emitting filaments are extremely thin (1.5 –4), implying magnetic fields of (8–16) $\times 10^{-9}$ T near the shock—tens to hundreds of times stronger than typical interstellar fields [?]. Unlike other remnants, Cas A also produces non-thermal X-ray emission from its reverse shock.

Cas A was IXPE's first science target, observed from January 11–29, 2022, with a total exposure of 9×10^5 s [?]. Vink et al. [?] derived the polarization degree distribution shown in [Figure 1: see original paper]. Assuming circular symmetry and summing over large regions, the overall 3–6 keV X-ray polarization degree is $(1.8 \pm 0.3)\%$ at 5σ confidence. After correcting for thermal emission contamination, the X-ray polarization degree becomes $(2.5 \pm 0.5)\%$, with the forward shock edge reaching $(4.5 \pm 1.0)\%$ [?]. The polarization angle measurements reveal a radial magnetic field structure, yet the total X-ray polarization degree is lower than the 5% measured in radio.

This result contradicts theoretical expectations. First, the maximum synchrotron polarization degree $\Pi_{\max}$ relates to photon spectral index Γ as $\Pi_{\max} = (\Gamma + 2/3)/(\Gamma + 5/3)$. Since Cas A's X-ray synchrotron spectrum is steeper than its radio spectrum, it should produce higher maximum polarization. Second, X-ray synchrotron emission originates from a narrow region $\leq 10^{17}$ cm downstream of the shock, which should reduce depolarization from magnetic field variations along the line of sight. Third, compression at the shock front should enhance the tangential magnetic field component, yet the observed polarization direction is tangential rather than the expected radial.

Besides line-of-sight effects, low polarization may arise from highly turbulent magnetic fields, consistent with isotropic turbulence models [?]. The low polarization could therefore result from isotropic magnetic turbulence or mixing of tangential fields near the shock front with radial fields further downstream on scales smaller than IXPE's angular resolution. While both X-ray and radio observations suggest radial magnetic fields dominate young supernova remnants overall, the origin remains uncertain. Two main hypotheses exist: (1) magnetohydrodynamic processes that stretch magnetic fields [?], and (2) a selection effect where particles accelerate more efficiently in quasi-parallel shock geometries, causing turbulent fields to appear radially aligned [?]. IXPE's results do not favor either hypothesis, but the confinement of X-ray synchrotron emission to regions $\leq 10^{17}$ cm demonstrates that radial magnetic field structures can indeed exist near shocks.

2.2 Tycho's Supernova Remnant

Tycho's supernova remnant (Tycho), the remnant of SN 1572, is 450 years old. High-resolution Chandra X-ray observations [?] and radio observations [?] reveal a thin synchrotron-bright ring at the shock, with small-scale "stripes" on the western side in the 4–6 keV band [?]. These structures are believed to be cosmic-ray acceleration sites, likely arising from ultra-high-energy electrons in amplified magnetic fields downstream of the shock.

IXPE observed Tycho in two periods: June 20–July 4, 2022, and December 21–25, 2022, with a total exposure of 9.9×10^5 s [?]. Ferrazzoli et al. [?] employed both small-scale and large-scale polarization searches. The small-scale search used 1 pixels (twice IXPE's angular resolution) to produce spatially resolved polarization images (see [Figure 2: see original paper]). These images show an overall tangential polarization pattern, indicating predominantly radial magnetic fields. The large-scale search computed polarization parameters for the entire remnant and selected regions, correcting for instrumental background and thermal emission to obtain average synchrotron polarization parameters. The overall synchrotron polarization degree is $(9.1 \pm 2.0)\%$, the shock ring region $(11.9 \pm 2.2)\%$, the southwestern "stripe" structure $(13.9 \pm 3.8)\%$ [?], and the western region reaches the highest value of $(23 \pm 4)\%$. In all significantly detected regions, polarization directions are predominantly tangential.

Tycho's X-ray synchrotron polarization exceeds its radio polarization (7%–8%) [?] and is higher than Cas A's X-ray polarization. This contrasts with Cas A's lower X-ray versus radio polarization and aligns with the three theoretical possibilities discussed in Section 2.1. Tycho's higher polarization compared to Cas A may indicate less turbulent magnetic fields or larger maximum turbulence scales. The X-ray polarization direction confirms radially dominated magnetic fields, consistent with radio observations and Cas A results.

3 Pulsar Wind Nebulae

Pulsars emit relativistic particle winds during their spin-down, which interact with their magnetic fields and surrounding interstellar medium to form pulsar wind nebulae. In young systems, these nebulae reside within supernova remnants. The relativistic outflow collides with supernova ejecta, creating a magnetohydrodynamic shock that terminates the wind, known as the termination shock, where particle acceleration likely occurs [?].

3.1 Crab Nebula

The Crab Nebula is among the most studied objects, with its high-energy radiation and particle acceleration processes receiving extensive attention. It is also the only object previously measured by traditional X-ray polarimetry methods. At optical wavelengths, the nebula spans 6 $×$4 , with non-thermal emission from synchrotron radiation and inverse Compton scattering by high-energy electrons and positrons detectable from radio to PeV energies [?].

IXPE observed the Crab Nebula's pulsar wind nebula and pulsar on February 21 and March 7, 2022, with a total exposure of 9.2×10^4 s [?]. The observations yield a total polarization degree of approximately 20% and a polarization angle of 145° [?]. The polarization structure (see [Figure 3: see original paper]) reveals a toroidal magnetic field morphology matching the X-ray emission, extending beyond the X-ray ring—consistent with magnetohydrodynamic model predictions for synchrotron radiation in the Crab Nebula [?]. The polarization degree distribution shows asymmetry relative to the nebular axis, more pronounced than in the intensity distribution. Optical polarization images exhibit similar trends [?], suggesting spatially varying turbulent magnetic fields or distorted field structures in faint outer regions.

The Crab Nebula's average X-ray polarization (~20%) agrees with previous measurements, with spatially resolved peaks reaching 46%–50% [?]—approximately double simple model predictions [?]. Theoretical models typically predict axisymmetric polarization patterns, but observations show asymmetry relative to the axis, indicating weaker and more spatially fragmented turbulence than predicted. Higher polarization at the ring's edges suggests highly ordered fields there, while optical observations show higher polarization in inner regions [?], implying different acceleration sites for optical- and X-ray-emitting particles. Since polarization degree depends on the ratio of turbulent to ordered magnetic energy while flux density depends on their sum, the stronger asymmetry in polarization suggests an inverse correlation between turbulent and ordered field strengths. If turbulent fields arise from Rayleigh-Taylor instabilities in magnetohydrodynamic flows, stronger fields would suppress turbulence [?]. Despite the recognized importance of magnetohydrodynamic turbulence, even the most sophisticated three-dimensional relativistic magnetohydrodynamic models struggle to reproduce the observed polarization distribution [?].

3.2 Vela Pulsar Wind Nebula

The Vela pulsar wind nebula, powered by the young pulsar B0833-45, resides within the Vela supernova remnant [?]. Previous X-ray observations revealed two prominent arc structures and perpendicular jet/counter-jet features [?, ?] (see [Figure 4: see original paper]b).

IXPE observed the Vela pulsar wind nebula from April 5–15 and April 21–30, 2022, with a total exposure of 8.6×10^5 s in the 2–8 keV band [?]. The measurements yield a total polarization degree of $(44.6 \pm 1.4)\%$ and a polarization angle of $(-50.0 \pm 0.9)^\circ$ (68.3% confidence) [?]. The latest IXPE results ([Figure 4: see original paper]a) show a toroidal magnetic field structure symmetric about the pulsar's spin axis projected on the sky, a symmetry also observed in radio but on larger spatial scales [?]. The X-ray polarization degree can exceed 60% [?], approaching the theoretical maximum for synchrotron radiation, while radio polarization reaches 60% in the nebula's outer regions [?].

The arcs and jets in pulsar wind nebulae are generally attributed to anisotropic pulsar winds generating toroidal magnetic fields in equatorial regions. In this scenario, the overall polarization angle should align with the nebula's symmetry axis, which IXPE confirms. The non-thermal radio and X-ray spectra indicate synchrotron dominance, and IXPE's high linear polarization measurement corroborates this. Model calculations predict maximum synchrotron polarization of approximately 70% for the Vela pulsar wind nebula; the observed maximum approaches this limit, indicating highly uniform magnetic fields with minimal turbulence. This suggests electrons accelerate in nearly turbulence-free, highly uniform fields— inconsistent with turbulent diffusive shock acceleration. Alternative mechanisms such as relativistic magnetic reconnection [?] may dominate particle acceleration in pulsar wind nebulae.

4 Summary and Outlook

IXPE's X-ray polarization imaging of young supernova remnants and pulsar wind nebulae reveals that particle acceleration zones in young remnants have turbulence-dominated magnetic fields, while the Vela pulsar wind nebula accelerates particles in a uniform field environment—contradicting turbulence-driven diffusive shock acceleration theory. Young supernova remnants also exhibit radial magnetic field structures near shocks, whose origin remains unclear. Additionally, the Crab Nebula's asymmetric polarization distribution relative to its axis challenges current magnetohydrodynamic simulations. Future IXPE observations of other bright pulsar wind nebulae will advance particle acceleration studies and refine magnetic turbulence models, while observations of additional young supernova remnants will help clarify the origin of radial magnetic fields and shock acceleration mechanisms.

China's upcoming eXTP mission will provide crucial data for long-standing questions in supernova remnant and pulsar wind nebula research through precise measurements of magnetic field distributions and polarized emission [**?**]. With an effective area of 900 cm^2—exceeding IXPE's—eXTP will enable more accurate polarization imaging of pulsar wind nebulae like the Crab Nebula, revealing magnetic configurations and cosmic-ray acceleration physics while exploring temporal variability. eXTP's polarimetric and spectroscopic studies of SN 1006 will investigate how particle injection direction relative to magnetic fields affects shock acceleration efficiency. While cosmic-ray acceleration at forward shocks is well-studied, reverse shock acceleration remains poorly understood; eXTP will provide magnetic field information at reverse shocks to study synchrotron intensity and field orientation. Magnetic field amplification in supernova remnants causes brightness variations in hot spots [**?**, **?**], and eXTP's polarimetric measurements of these features will constrain turbulence scales and investigate amplification mechanisms.

As imaging technology advances, next-generation X-ray polarization telescopes will achieve superior performance through larger effective areas for enhanced sensitivity, higher spatial resolution for detailed structure analysis, and broader energy coverage. These improvements will yield more comprehensive X-ray polarization data on supernova remnants and pulsar wind nebulae, further illuminating the physical mechanisms of relativistic shock particle acceleration.

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