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

Authors: Luo Tianxian, Zhou Ping

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Abstract

High-energy particles in young supernova remnants and pulsar wind nebulae can produce X-ray emission through synchrotron radiation. Polarization measurements of this radiation help reveal the properties of magnetic fields in particle acceleration regions, thereby facilitating investigations into particle acceleration mechanisms. The first X-ray polarimetric imaging satellite, launched at the end of 2021, has already revealed X-ray polarization images of several young supernova remnants and pulsar wind nebulae. Observations show that Cassiopeia A and Tycho's supernova remnant exhibit relatively low polarization degrees, with average values of approximately 2.5% and 9%, respectively; whereas the Crab Nebula and Vela pulsar wind nebula display relatively high polarization degrees, with average values of approximately 20% and 45%, respectively. These results indicate that magnetic fields in pulsar wind nebulae are relatively ordered, while 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 utilization of IXPE becomes more widespread and additional telescopes such as China's under-construction enhanced X-ray Timing and Polarimetry detector (eXTP) are deployed, the magnetic field configurations and particle acceleration models of the aforementioned two classes 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 emission through synchrotron radiation. Polarimetric measurements of this radiation help reveal the properties of magnetic fields in particle acceleration regions, thereby facilitating studies of particle 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 Cassiopeia A and Tycho's supernova remnant exhibit low polarization degrees, with average values of approximately 2.5% and 9%, respectively. In contrast, 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. In the future, as IXPE observations become more widespread and additional telescopes such as China's planned enhanced X-ray Timing and Polarimetry (eXTP) detector come online, the magnetic field configurations and particle acceleration models for these two classes of objects will be further constrained.

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

1. Introduction

Polarization of electromagnetic radiation can reveal the magnetic field configuration within and near the radiation source, as well as the properties of radiative transfer. 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. The polarization angle is measured from north, positive toward east. Both pulsar wind nebulae and supernova remnants typically emit synchrotron radiation. The polarization direction of synchrotron radiation is related to the projected direction of the local magnetic field on the sky, while the polarization degree depends on the degree of magnetic field ordering: more ordered fields produce higher polarization. Consequently, synchrotron polarization reflects the geometric configuration and turbulence level 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 with 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 closer to the particle acceleration region. Therefore, X-ray polarization can reveal more about the magnetic field properties in particle acceleration zones, helping us to better understand particle acceleration mechanisms.

In 1971, observations of the Crab Nebula using an Aerobee-350 sounding rocket first revealed a possible X-ray polarization signal [?]. Subsequent measurements with the OSO-8 satellite, which carried two X-ray polarimeters, confirmed that the Crab Nebula's X-ray emission exhibited a polarization of $(16.1 \pm 1.4)\%$ [?]. Traditional X-ray polarimetry typically relied on Thomson scattering, Compton scattering, or Bragg crystal diffraction, exploiting their dependence on linear polarization. However, these methods suffered from poor sensitivity, yielding reliable results only for relatively bright sources and proving unsuitable for extended sources. This limitation arose because extended sources often contain multiple regions with different polarization properties, requiring telescopes with spatial resolution capabilities. Recent advances in X-ray polarization imaging technology have resolved this long-standing challenge.

The current leading X-ray polarization imaging technology employs gas pixel detectors (GPDs), which utilize the photoelectric effect in thin gas layers. The ejected photoelectron's direction aligns primarily with the electric field vector of the incident photon. By recording the photoelectron's interaction track using finely structured electrodes, and analyzing the initial portion of the track that contains information about the ejection direction, the polarization of incoming photons can be determined [?]. Compared to traditional methods, GPDs offer substantially improved sensitivity, promising to detect X-ray polarization from thousands of Galactic and extragalactic sources with much greater detail [?].

The advent of GPD technology has spawned several new 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 [?], and eXTP has not yet launched, leaving IXPE as the only operational mission. IXPE was launched in December 2021, carrying three GPDs and achieving the first imaging observations of X-ray polarization.

IXPE consists of three identical X-ray telescopes, each comprising an X-ray mirror module and a detector unit. The detector units are located at the focal plane of the optical system, with each core being a polarization-sensitive GPD. Each detector unit has an effective mirror area of 166 cm^2 at 2.3 keV and can perform polarization and spectral 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 institutions from more than 20 countries including Italy and Germany, plans to carry four instruments covering the 0.5–30 keV band: the Spectroscopic Focusing Array (SFA), the Polarimetry Focusing Array (PFA), the Large Area Detector (LAD), and the Wide Field Monitor (WFM). The PFA employs GPD technology with an angular resolution better than 30 and operates 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. Beginning in 2022, IXPE has observed several supernova remnants and pulsar wind nebulae, yielding new insights into the magnetic fields of these objects. This paper introduces the scientific questions addressed by X-ray polarization imaging for these two classes of objects, presents new discoveries from IXPE, and concludes with prospects for future X-ray polarization studies.

2. Supernova Remnants

Supernova remnants are structures formed when supernova explosion shocks sweep through the interstellar medium. Most Galactic supernova remnants have been discovered through radio emission, which primarily originates from synchrotron radiation by relativistic electrons at GeV energies [?]. To detect radiation from higher-energy relativistic electrons, observations at higher frequencies are required. In 1995, Koyama et al. [?] discovered 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 radiation from filamentary structures has also been detected in several young supernova remnants, including Cassiopeia A, Tycho's supernova remnant, and G347.3–0.5 [?]. Currently, particle acceleration to relativistic energies in supernova remnants is widely believed to occur through diffusive shock acceleration [?]. In this framework, magnetic field amplification mechanisms are required for supernova remnants to accelerate cosmic rays to the knee of the cosmic ray spectrum, and highly turbulent magnetic fields represent one possible mechanism [?]. Since X-ray synchrotron radiation in young supernova remnants originates from very-high-energy particle acceleration zones, X-ray polarization observations serve as an important tool for investigating the magnetic field geometry and turbulence properties in nearby active acceleration regions.

2.1 Cassiopeia A (Cas A)

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

Cassiopeia A was IXPE's first science target, observed from January 11–29, 2022, with a total exposure time 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 polarization degree in the 3–6 keV band is $(1.8 \pm 0.3)\%$ at 5σ confidence. After correcting for the substantial thermal radiation contribution, the X-ray polarization degree becomes $(2.5 \pm 0.5)\%$, while the forward shock edge shows about $(4.5 \pm 1.0)\%$ [?]. As shown in [Figure 1: see original paper], the X-ray polarization angle measurements indicate the presence of radial magnetic fields in Cassiopeia A, with the total X-ray polarization degree being lower than the 5% measured in the radio band.

This result contradicts previous theoretical expectations. First, the maximum synchrotron polarization degree $\Pi_{\max}$ depends on the photon spectral index as $\Pi_{\max} = (\alpha + 1)/(\alpha + 5/3)$. Since Cassiopeia A's X-ray synchrotron spectrum is steeper than its radio spectrum, it should produce a higher maximum polarization degree. Second, X-ray synchrotron radiation in Cassiopeia A 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. Additionally, compression at the shock front should enhance the tangential magnetic field component, leading to an expected radial polarization direction, whereas the observed polarization direction is tangential.

Besides line-of-sight effects, the low polarization degree may arise from highly turbulent magnetic fields, consistent with models of isotropic magnetic turbulence [?]. Therefore, the low polarization could result from either isotropic magnetic turbulence or observational mixing of tangential fields near the shock front with more downstream radial fields on scales smaller than IXPE's angular resolution. Although both X-ray and radio observations infer that young supernova remnants are dominated by radial magnetic fields overall, the origin of this field orientation remains uncertain, with two main hypotheses: (1) magnetohydrodynamic processes that stretch magnetic fields [?]; and (2) a selection effect where particles may be accelerated more efficiently in environments with magnetic fields quasi-parallel to the shock propagation direction, causing even turbulent fields to appear radially aligned in observations [?]. IXPE's results do not favor either hypothesis, but the confinement of X-ray synchrotron radiation 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) is the remnant of the historical supernova SN 1572 and is 450 years old. High-resolution Chandra X-ray Observatory observations [?] and radio observations [?] both reveal a thin synchrotron radiation bright ring at the shock, with small-scale structures called "stripes" on the western side of the ring in the 4–6 keV band [?]. These structures are generally believed to be cosmic ray acceleration zones, possibly arising from X-ray radiation emitted by ultra-high-energy electrons in magnetic field amplification regions downstream of the shock.

IXPE observed Tycho during two periods: June 20–July 4, 2022, and December 21–25, 2022, with a total exposure time of approximately 9.9×10^5 s [?]. Ferrazzoli et al. [?] employed two analysis approaches: small-scale and large-scale polarization searches. The small-scale search used 1 pixels (twice IXPE's angular resolution) to compute polarization degree and direction for each pixel, producing a spatially resolved polarization image (see [Figure 2: see original paper]). This image shows an overall tangential polarization pattern, indicating a predominantly radial magnetic field orientation. The large-scale search calculated polarization parameters for the entire remnant and selected regions, deriving average synchrotron radiation polarization parameters after subtracting instrumental background and thermal emission. The overall synchrotron polarization degree is $(9.1 \pm 2.0)\%$, the shock ring region shows $(11.9 \pm 2.2)\%$, the southwestern "stripe" structure exhibits $(13.9 \pm 3.8)\%$, and the western region reaches the highest value of $(23 \pm 4)\%$ [?]. In all significantly detected regions, the polarization direction is largely tangential.

Tycho's X-ray synchrotron polarization degree is higher than its radio polarization of 7%–8% and exceeds that of Cassiopeia A. This contrasts with Cassiopeia A's case where X-ray polarization is lower than radio, and aligns with the three theoretical possibilities discussed in Section 2.1. Furthermore, Tycho's higher polarization degree compared to Cassiopeia A may result from either less turbulent magnetic fields or larger maximum turbulence scales in Tycho. The X-ray polarization direction indicates a predominantly radial magnetic field arrangement, consistent with radio observations and with results from Cassiopeia A.

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, pulsar wind nebulae generally reside within supernova remnants. The interaction between the relativistic outflow and supernova ejecta produces strong magnetohydrodynamic shocks that terminate the pulsar wind nebula, known as the termination shock. Particle acceleration in pulsar wind nebulae may occur at this termination shock location [?].

3.1 Crab Nebula

The Crab Nebula is one of the most studied objects, with its high-energy radiation and particle acceleration processes receiving widespread attention. It is also the only object measured by traditional X-ray polarimetry methods. At optical wavelengths, the Crab Nebula spans 6 × 4 , with its non-thermal radiation arising 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 time of approximately 9.2×10^4 s [?]. The observations yield a total polarization degree of about 20% and a polarization angle of 145° for the pulsar wind nebula [?]. The derived polarization structure ([Figure 3: see original paper]) reveals a toroidal magnetic field morphology that matches the X-ray emission, with the magnetic field's toroidal extent exceeding the X-ray emission ring—consistent with magnetohydrodynamic model calculations of synchrotron radiation in the Crab Nebula [?]. [Figure 3: see original paper] shows that the Crab Nebula's polarization degree distribution exhibits asymmetry relative to the axis, while the intensity asymmetry is relatively weaker. Optical polarization images show similar trends [?], suggesting the presence of spatially varying turbulent magnetic fields within the pulsar wind nebula or distorted magnetic field structures in the faint outer regions.

The Crab Nebula's average X-ray polarization degree (~20%) agrees with previous measurements, with the maximum spatially resolved polarization reaching 46%–50% [?]—approximately twice that predicted by simple models [?]. Theoretical models generally predict a polarization pattern symmetric about the pulsar wind nebula's axis, whereas observations show asymmetry, indicating that the turbulent magnetic field is not as strong as predicted and is more sporadically distributed. Higher polarization degrees at the ring's edge suggest highly ordered magnetic fields there. In contrast, optical observations show higher polarization in the inner region than at the ring edge [?], indicating that particles emitting optical and X-ray radiation may be accelerated at different locations. 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 than in flux suggests an anti-correlation between turbulent and ordered magnetic field strengths. If turbulent fields originate from Rayleigh-Taylor instabilities in magnetohydrodynamics, stronger fields would more effectively suppress turbulence [?]. Although magnetohydrodynamic turbulence is thought to play an important role, even the most sophisticated three-dimensional relativistic MHD models to date [?] struggle to explain the observed polarization distribution in the Crab Nebula.

3.2 Vela Pulsar Wind Nebula

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

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

The arcs and jet structures in pulsar wind nebulae are generally believed to result from toroidal magnetic fields generated in the equatorial region of anisotropic pulsar winds. In this scenario, the overall polarization angle should be parallel to the nebula's symmetry axis, which IXPE observations support. The non-thermal radio and X-ray spectra of the Vela pulsar wind nebula indicate that synchrotron radiation dominates, and IXPE's measurement of high linear polarization in X-rays confirms this conclusion. Model calculations yield a maximum synchrotron polarization degree of approximately 70% for the Vela pulsar wind nebula, and the observed maximum polarization is very close to this limit, indicating highly uniform magnetic fields with only minimal turbulence. This suggests that electrons in pulsar wind nebulae are accelerated in nearly turbulence-free, highly uniform magnetic fields— inconsistent with turbulent diffusive shock acceleration. Alternative mechanisms, such as relativistic magnetic reconnection [?], may therefore dominate particle acceleration in pulsar wind nebulae.

4. Summary and Outlook

IXPE's X-ray polarization imaging observations of young supernova remnants and pulsar wind nebulae demonstrate that particle acceleration regions in young supernova remnants have turbulence-dominated magnetic fields, while particles in the Vela pulsar wind nebula are accelerated in a uniform magnetic field environment—contradicting turbulence-driven diffusive shock acceleration theory. Additionally, radial magnetic field structures exist near supernova remnant shocks, though the mechanism producing this field orientation remains unclear. Furthermore, the Crab Nebula's asymmetric polarization distribution relative to its axis also disagrees with current magnetohydrodynamic simulations. Future IXPE observations of other bright pulsar wind nebulae will advance studies of particle acceleration mechanisms and improve existing magnetic turbulence models, while observations of more young supernova remnants will help us understand the origin of radial magnetic field structures and how particles are accelerated at shocks.

Looking ahead, China's eXTP mission is expected to provide crucial data for long-standing questions in supernova remnant and pulsar wind nebula research through precise measurements of magnetic field distributions and polarized radiation [**?**]. Specifically, with an effective area of 900 cm^2—larger than IXPE—eXTP will enable more accurate polarization imaging of pulsar wind nebulae like the Crab Nebula. This polarization information will reveal magnetic field configurations, help infer the physical mechanisms of cosmic ray acceleration, and enable exploration of possible temporal variations. Polarimetric and spectroscopic studies of the supernova remnant SN 1006 with eXTP will investigate how the injection direction relative to the magnetic field affects shock acceleration efficiency. While cosmic ray acceleration at forward shocks in supernova remnants has been extensively studied, acceleration at reverse shocks remains poorly understood. eXTP will provide magnetic field information at reverse shocks to study synchrotron radiation intensity and field orientation there. Magnetic field amplification in supernova remnants can cause brightness variations in hot spots [**?**, **?**], and eXTP's polarization measurements of these hot spots will help estimate magnetic turbulence scales and study field amplification mechanisms.

As imaging technology advances, next-generation X-ray polarization imaging telescopes will offer improved capabilities, such as larger effective areas for enhanced sensitivity, higher spatial resolution for resolving structures, and broader energy ranges. These developments will yield more X-ray polarization information about supernova remnants and pulsar wind nebulae, further illuminating the physical mechanisms behind relativistic shock particle acceleration.

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