32. Evaluation of the magnetic field structure in the "West bay" of the Crab Nebula through IXPE long observation and simulations

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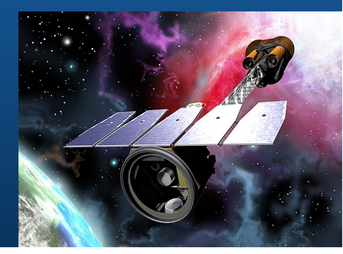
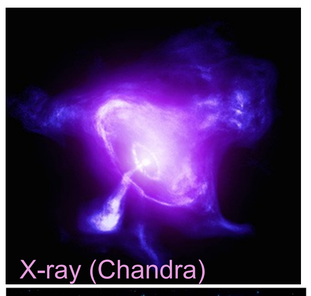


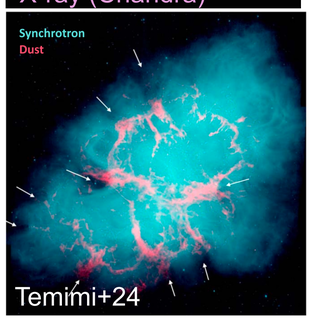
Abstract :
The IXPE is the first satellite to perform polarimetric imaging observations in soft X-rays. With the IXPE, we can constrain the magnetic field in the particle acceleration region of the crab pulsar (PSR) and pulsar wind nebula (PWN). This will help us understand the particle acceleration and transport. In Wong+ 2024, we divided the torus (in PWN) into East, West, North, and South regions and investigated the spectral and polarimetric properties. We found the spectrum was hard toward the west where PD was lower than others. Here, we're investigating a western Bay-like structure, called "West Bay" (Seward+ 2006). Spectral and polarimetric analysis shows PD decreases toward the bay and PA changes abruptly at the bay. Through the polarization modeling, we found the PD decreases linearly from 35% to 5% toward the bay, and the PA changes abruptly from 160° to 80° on the way to the bay. These results suggest that loop-like filaments surrounding the PWN blocks the PW.

Crab Nebula and Radiation from PWN

- Crab Pulsar (PSR) + Pulsar Wind Nebula (PWN)
  - PSR (P = 33 ms) at the center
  - d = 2 kpc, L = 5 × 10^{38} erg/s
- Magnetic field (B) is important in particle acceleration and radiation.
  - Spatial polarization of X-rays will reveal the B structure close to the acceleration region.
- Optical and IR show structures such as bays and filaments (origin unknown).

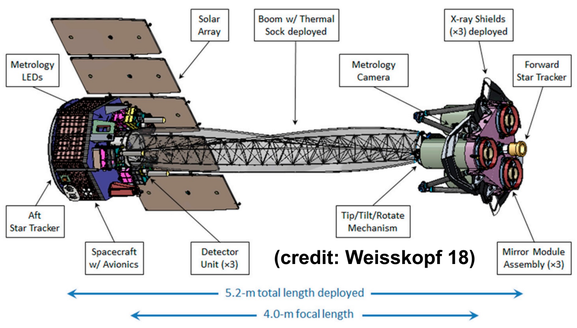
➢ **Constrain the B structure to understand the acceleration and cooling mechanism.**





Imaging X-ray Polarimetry Explorer (IXPE)

- Launched in December 2021.
- **First satellite to perform polarimetric imaging observations in soft X-rays.**
  - 3 x (mirror + detector)
  - Energy : 2-8 keV
  - Angular resolution (HPD) : ≤ 25”
  - Field of View : 12.9’ x 12.9’
  - Modulation factor (μ_{100}) : 15 % @ 2 keV, 55 % @ 6 keV



- Observed “Crab” about 280 ks in 2022-2024
- **Evaluate stokes parameters for each event.**

$$i_k \equiv 1, \qquad q_k \equiv 2\cos 2\phi_k, \qquad u_k \equiv 2\sin 2\phi_k$$

(Stokes parameter for a photon)

$$I = \sum_{k=1}^{N} i_k = N, \quad Q = \sum_{k=1}^{N} \frac{q_k}{\mu}, \quad U = \sum_{k=1}^{N} \frac{u_k}{\mu}$$

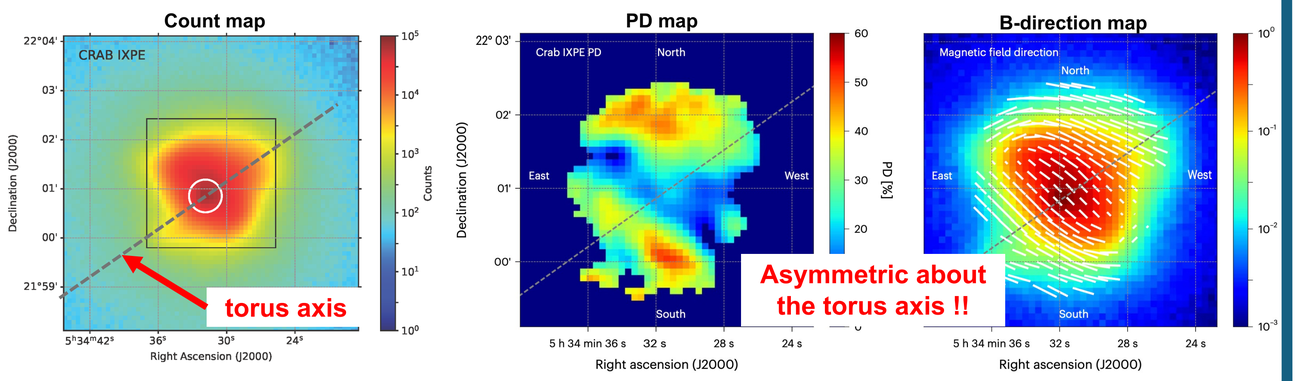
(Stokes parameter for all photon)

$$\mathrm{PD} = \frac{\sqrt{Q^2+U^2}}{I}, \quad \mathrm{PA} = \frac{1}{2}\arctan\left(\frac{U}{Q}\right)$$

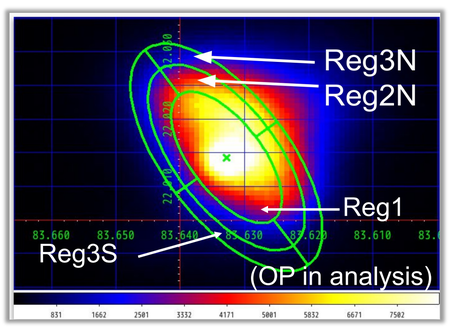
Polarization degree = PD
Polarization angle = PA

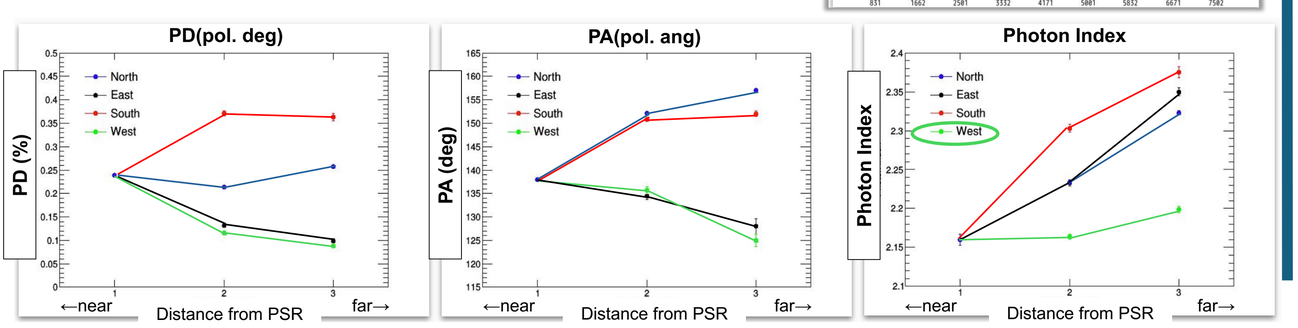
Past spectral polarimetric study (Bucciantini+23, Mizuno+23, Wong+24)

- First polarization map in soft X-rays (Bucciantini+23, Mizuno+23).
  - (left) The count map is generally symmetric about the X-ray torus axis.
  - **(middle, right) PD and B-direction are asymmetric about the torus axis.**



- Divided the torus into E, W, S, N regions to investigate spectral and polarimetric properties with polarization leakage correction.
  - (left) PD is high in N&S and low in E&W.
  - (middle) PA deviates in diametric ways btw. N&E and btw. S&W
  - (right) **Spectrum remains hard toward west.**



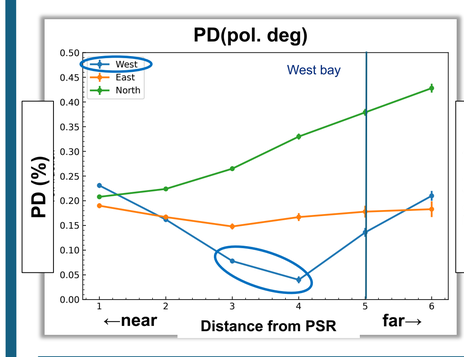


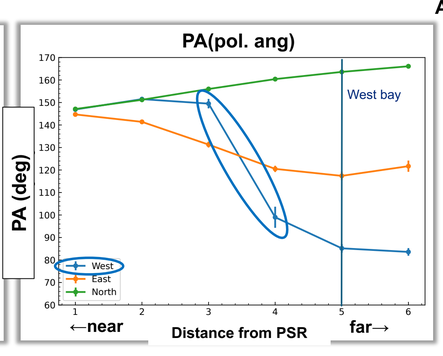
In depth Analysis of West Bay

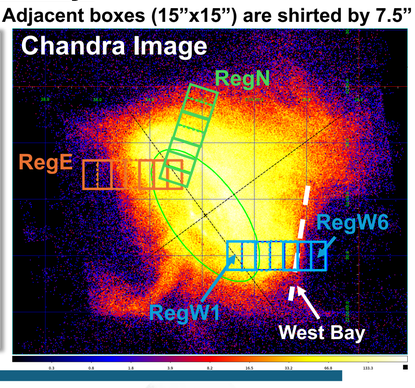
- The origin of “West Bay” (Seward+ 06) is unknown.
- Defined 6 regions in E, W, N and compared the spectral and polarimetric properties.
  -> found distinctive properties in West
  - (left) PD decreases up to reg 4, then PD recovers to >10% in regs 5&6.
  - (right) PA abruptly changes btw. regs 3&4. B-direction is parallel to bay in regs 5&6.

➢ **These results suggest an environmental effect in West bay.**

Adjacent boxes (15”x15”) are shirted by 7.5”



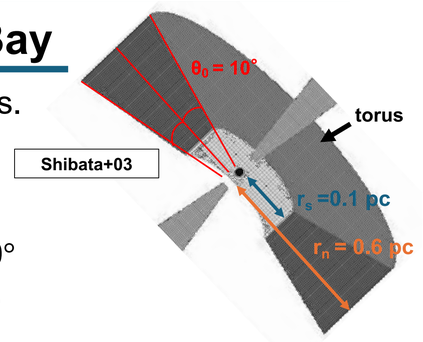




Discussion about 3D Structure of West Bay

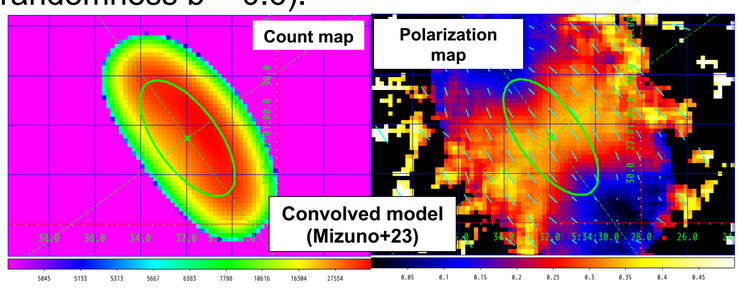
First, we verified the geometrical polarization model of torus.

- The PWN is a simple equatorial wedge.
  - r_s = 0.1 pc, r_n = 0.6 pc, θ_0 = ± 10°
  - flow velocity v = 0.2c (c: speed of light)
  - wedge position and inclination angles: 126.3° and 63.0°
- B distribution (radial profile) is the KC model (σ = 0.003).
- Assumed toroidal and turbulent B (randomness b = 0.6).



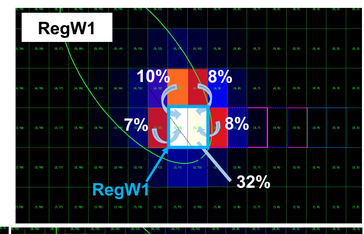
- Convolved the model with IXPE response
  - **This model is insufficient.**

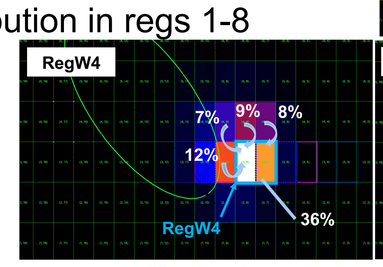
➢ Need a bay structure to create the model matched with observations.

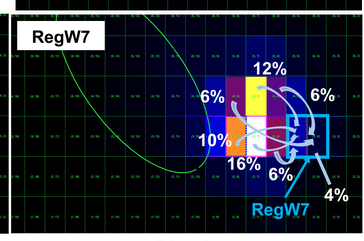


Evaluating the photon leakage:

- We evaluated the photon leakage due to IXPE’s PSF using ixpeobssim simulation (V31.0.1). Specifically, we:
  - Defined **1170 pixels (7.5” x 15”)** covering PWN
  - Convolved the Chandra image with IXPE’s PSF
  - Made the photon leakage distribution in regs 1-8
- Intrinsic properties of PD/PA
  - **PD decreases from reg1-4**
  - **PA already changed in reg4**
    - ➢ Improve the model with the bay’s B

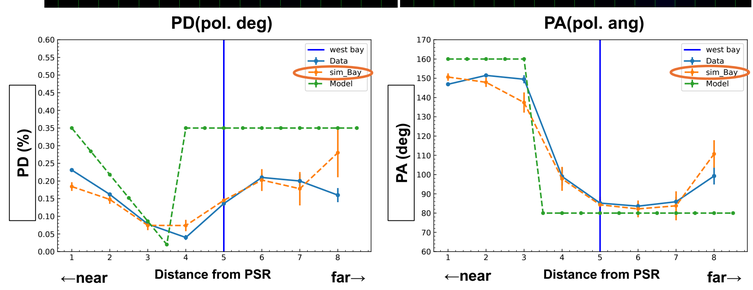






Improving a model:

- **Convolved PD/PA** are qualitatively compatible with **observations.**
  - **PD linearly decreases from 35% to 5%** toward bay up to reg 3.5
  - PA abruptly changes, btw. 3&4, from 160° to 80° (parallel to bay).

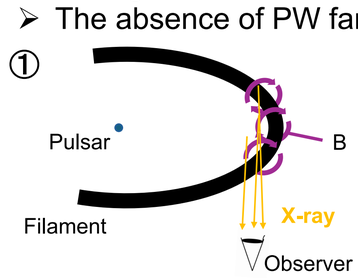


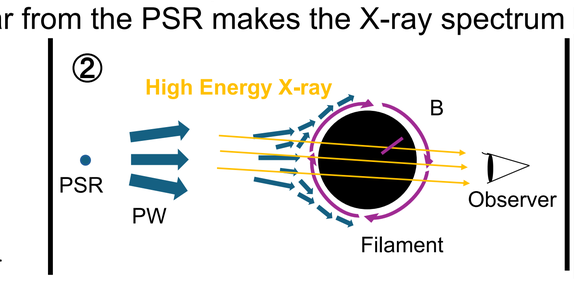
3D structure of West bay:

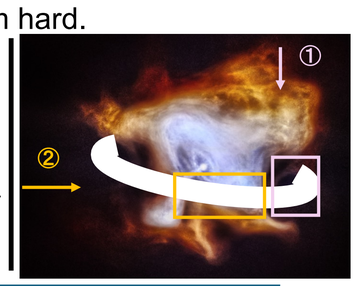
- **We suggest that loop-like filament surrounds the Crab PWN and B wraps around it.**

① Filament runs in line-of-sight and blocks PW at the West Bay.
  ➢ The B-direction at the boundary btw. PWN and Bay is parallel to the north-south direction.

② The foreground filament blocks the PW coming toward us and changes its direction.
  ➢ Changes of the B-direction causes depolarization.
  ➢ The absence of PW far from the PSR makes the X-ray spectrum hard.







Summary

- We evaluated the B structure of West Bay through IXPE observations and simulations.
  - We created a polarization model taking account of IXPE’s PSF.
    - The convolved model is compatible with IXPE observation.
  - We conclude that loop-like filament surrounding the Crab PWN causes the asymmetric PD/PA with respect to torus axis.

Reference: F. D. Seward et al 2006 ApJ, **652**1277, Weisskopf, M. C. (2018). Galaxies, 6(1), 33, Baldini et al Astroparticle Physics, 133, 102628., Bucciantini et al Nature Astronomy, 7(5), 602-610, Mizuno et al PASJ, 75(6), 1298-1310, Wong et al 2024 ApJ, **973** 172, Shibata et al K. 2003, MNRAS, 346, 841,