Polarimetry with the Soft Gamma-ray Detector onboard ASTRO-H

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Introduction: Polarimetry of Cyg X-1 (1)

- VLBA/LVA reveal a radio-emitting jet from Cyg X-1. PA is -21~-24 deg.
- Polarization is a powerful probe to study geometries of astrophysical sources (and break model degeneracy)
- How about the X-ray/γ-ray polarimetry of the object?

Radio Jet
Stirling+01
(PA: -21~-24 deg.)

Disk reflection
Comptonization

Radio

\( P_{jet} = 10^{36} - 10^{37} \text{ erg/s} \)
\( 3\% - 50\% \text{ of } L_X \)

\( (\text{Gallo+05}) \)
Introduction: Polarimetry of Cyg X-1 (2)

- How about the X-ray/γ-ray polarimetry of the object?
- Previous X-ray and γ-ray polarimetry suffers large uncertainty. Interpretation (w.r.t. radio jet) not so straightforward.
- We need better sensitivity in polarization.

Radio

Radio Jet

Stirling+01

(\( \text{PA: } -21\sim -24 \text{ deg.} \))

X-ray

Comptonization

Disk reflection

Long+80

hint of \( \text{pol.}@2.6/5.2 \text{ keV (disk?)} \)

\( \text{PA: } 162+/\text{-}13 \text{ deg.} \)

γ-ray

\( \text{Laurent+11} \)

\( \text{pol.}@E>400 \text{ keV (jet?)} \)

\( \text{PA: } 140+/\text{-}15 \text{ deg.} \)
Polarization Sensitivity

• Minimum Detectable Polarization (pol. degree distinguishable from statistical fluctuation)

\[ MDP = \frac{4.29}{M \times R_S} \sqrt{\frac{R_S + R_B}{T}} \]

99% Confidence

- Larger \( M \)
- Larger \( R_S \) (Larger \( A_{eff} \))
- Smaller \( R_B \)

\( M : \) Modulation Factor
\( R_S : \) Source rate
\( R_B : \) Background rate
\( T : \) Obs. time

\( A-H \ (2014-\) \ SGD achieves large \( M \) and small \( R_B \)
ASTRO-H (2014~) SGD

- Si-CdTe Compton Camera + BGO shielded
- Constrain incident angle using Compton kinematics
  - efficient background suppression ($\theta$-cut)

Background Level

\[
\cos \theta = 1 + \frac{m_e c^2}{E_1 + E_2} - \frac{m_e c^2}{E_2}
\]

Suzaku HXD-GSO (Data)

0.1 Crab

Astro-H SGD

BG$\leq$100 mCrab

Tajima+ 10 Proc. SPIE

Compton Scat.

Photo-abs.
ASTRO-H SGD as a Polarimeter

- **Si-CdTe Compton Camera + BGO shield**
  - Constrain incident angle using Compton kinematics
    - efficient background suppression ($\theta$-cut)
    - polarization measurement ($\phi$-measurement)

\[
\cos \theta = 1 + \frac{m_e c^2}{E_1} - \frac{m_e c^2}{E_2}
\]

Tajima+ 10
Proc. SPIE

Lei+97 (Concept of Compton polarimeter)
Performance Verification (1)

- Beam test at Spring-8 (Synchrotron facility in Japan)
- Use 90-degree scattered photons to reduce the beam intensity (~170 keV, 92.5% polarized)
- Detectors were rotated to study systematic effects

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250 keV (>99.9%)

170 keV (92.5%)

SGD prototype

1 layer DSSD

4 layers CdTe (Btm)

4-sides CdTe

Takeda+ 10, NIMA
Performance Verification (2)

- Beam test at Spring-8 (Synchrotron facility in Japan)

**A: polarized beam**
- Data
- Simulation

**B: non-polarized beam**
- (Data=0deg+90deg runs)

- Modulation Curve = \( \frac{A}{B} \)
- \( M=0.82 \) is consistent with the expectation (0.855) within systematic uncertainty of 3% => verifying the detector concept and simulation
- \( M_{100} \approx 0.58 \) and efficiency \( \approx 10\% \) w/ flight configuration

Takeda+ 10, NIMA
Background Simulation (1)

- Background estimation and reduction is a key for the SGD polarimetry
- SAA protons (radioactivation) and albedo neutrons (elastic scattering) are dominant sources of the BG
- We develop Monte-Carlo simulator to study BG

Yamada
Background Simulation (2)

- Background estimation and reduction is a key for the SGD polarimetry.

**CdTe**: data vs. simulation
(active material w/ large Z)

150 MeV protons (typical for SGD)

CdTe or FC
(Murakami+03)

- Identify several lines (radioisotopes) in both data and sim.
- Verify Simulation through a comparison with the beam test data

Mizuno+ 10, proc SPIE
Background Simulation (3)

- Background estimation and reduction is a key for the SGD polarimetry.

**Fine Collimator:** data vs. simulation

150 MeV protons (typical for SGD)

(material inside FOV)

Cooling time: 2 d

Cooling time: 13 d

CdTe or FC

(Murakami+03)

Mizuno, Nakajima+

- Identify several lines (radioisotopes) in both data and sim.
- Verify Simulation through a comparison with the beam test data.
Crab Nebula Polarimetry (Current Status)

- Great success by INTEGRAL SPI/IBIS, but large error (~10 deg in PA) prevents unambiguous interpretation.
SGD Polarimetry of the Crab Nebula

- Precise measurement of pol. angle
  - comparison with a pulsar rot. axis within a few degree accuracy

INTEGRAL IBIS
Modulation Curve@200-800 keV
(pol. deg. >88%
PA=122+-7 deg.)

SGD Simulation, 100 ks obs.
50% polarization @80-300keV assumed

\[ Q = 0.58 \]
\[ \mu = 0.505 \pm 0.009, \phi_0 = -0.1 \pm 0.5 \text{ [deg]} \]

Forot+08
Tanaka
Cyg X-1 Polarimetry (Current Status)

- How about the X-ray/\(\gamma\)-ray polarimetry of the object?
- Previous X-ray and \(\gamma\)-ray polarimetry suffers large uncertainty. Interpretation (w.r.t. radio jet) not so straightforward.

Radio

Radio Jet
Stirling+01
(PA: -21\,-\,-24 \,\text{deg.})

\(\gamma\)-ray

Laurent+11
pol.@E>=400 keV (jet?)
PA: 140+/\,-15 \,\text{deg.}

X-ray

Comptonization
Disk reflection

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PA: 162+/\,-13 \,\text{deg.}
SGD Polarimetry of Cyg X-1

- Assume jet component is contaminated by disk Comptonization in the SGD band (PD<=20%)
  - still able to disclose weak polarization hidden in Comptonization down to 100 keV

INTEGRAL IBIS Modulation Curve@250-400 keV (PD<=20%

10% polarization @100-180 keV

ΔPA~2 deg

17% polarization @180-330 keV

ΔPA~3 deg

Laurent+11

Tanaka
Summary

• Polarization measurement can place constraints on source geometry (*qualitatively new information*)
• Astro-H SGD is a Compton polarimeter. It is well validated through experimental test and simulation.
• The SGD is able to precisely measure polarization from Crab Nebula and Cyg X-1. Can constrain magnetic field (and disk) direction within a few degree.

Thank you for your Attention
Backup Slides
A Jet-blowing Ring

- Large scale ring-like structure inflated by the inner jet

Gallo+05

$\sim 5$ pc ring @ 1.4 GHz

$P_{\text{jet}} = 10^{36} - 10^{37}$ erg/s

milliarcsec-scale radio jet
X-ray/Gamma-ray Polarimetry

- Why polarization? (1) place constraints on source geometries (2) break model degeneracy
  - Synchrotron emission (magnetic field)
  - Compton up-scattering radiation (see photons, disk)
  - Pol. due to QED or general relativity (constraints on fundamental physics and compact object)

Magnetic field, Accelerated electrons
Pulsar emission model, QED
X/γ-ray pol. not subject to Faraday rotation/depolarization
Measuring energy dependent polarization is crucial to disentangle emission mechanisms. Transition from one polarization generation process to another may occur over broad energy range.

- **Disk reflection model (Matt+93)**
  - Polarization vector perpendicular to disk
  - Plot shows polarization degree against photon flux for different energies.

- **Blazar model (Poutanen94)**
  - Photon flux and degree for synchrotron, IC, total emission.
  - Note: polarization may be low in EC

**Figure:**
- Graphs illustrating polarization as a function of photon energy.