X-ray Polarimetry with a Micro-Pattern Gas Detector

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Exploration of the Universe Division
NASA/Goddard Space Flight Center
Overview

- Science Drivers for X-ray Polarimetry
- Previous X-ray Polarimeter Designs
- The Photoelectric Effect and Imaging Tracks
- Micro-pattern Gas Polarimeter Design Concept
- Preliminary Results
- Plans for the Future
The Missing Link?

Imaging: Chandra

Timing: RXTE

Spectroscopy: XMM Chandra, Con-X

Polarimetry?
Science Drivers

- How important is particle acceleration in supernova remnants?
- How is energy extracted from gas flowing into Black holes?
- What happens to gas near accreting Neutron Stars?

The degree, direction and energy dependence of the polarisation provides a measure of the non-thermal electron distribution and possible magnetic field configurations.
Unified Theory?

- Molecular Torus
- Central Engine
- Radio Lobe
- Relativistic Jet
- Observer sees Blazar
- Observer sees Quasar
- Observer sees Radio Galaxy
- Aspect Angle
The Crab Nebula

Radio: VLA

Infra-red: Keck

Optical: Palomar

X-ray: Chandra
Potential Sources

† Sources bright enough for a rocket flight observation in yellow

<table>
<thead>
<tr>
<th>ROSAT Source Name</th>
<th>SIMBAD or Common Name</th>
<th>Measured by OSO 8</th>
<th>Source FOM = cnts*hr^-2</th>
<th>Source Type</th>
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<tbody>
<tr>
<td>1RXS J170248.5-484719</td>
<td>4U 1658-48 (V* V821 Ara)</td>
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<td>23.0</td>
</tr>
</tbody>
</table>
**X-ray Polarimeters**

- Bragg Crystal
- Thomson Polarimeter

![Diagram of X-ray Polarimeters](image)
The Photoelectric Effect

- The photoelectron is ejected with a $\cos^2 \theta \sin^2 \phi$ distribution aligned with the E-field of the incident X-ray.
- The photoelectron loses its energy with elastic and inelastic collisions creating small charge clouds.

$$P(\phi) d\phi = \cos^2 \phi d\phi$$
Photoelectron Emission Angle

Direction of the major axis of the second moment, $M$, of the charge distribution:

\[
X_{rms} = \sqrt{\sum_{ij} E_{ij}^2 \left( \frac{\sum_{ij} E_{ij}}{\sum_{ij} E_{ij}} \right)^2}
\]

\[
Y_{rms} = \sqrt{\sum_{ij} E_{ij}^2 \left( \frac{\sum_{ij} E_{ij}}{\sum_{ij} E_{ij}} \right)^2}
\]

\[
\langle XY \rangle_{rms} = \frac{\sum_{ij} E_{ij} j \times \left( \frac{\sum_{ij} E_{ij} i}{\sum_{ij} E_{ij}} \right) \left( \frac{\sum_{ij} E_{ij} j}{\sum_{ij} E_{ij}} \right)}{\sum_{ij} E_{ij}^2 \left( \frac{\sum_{ij} E_{ij}}{\sum_{ij} E_{ij}} \right)^2}
\]

\[
\phi = \frac{1}{2} \tan^{-1} \left( \frac{-2 \langle XY \rangle_{rms}}{\frac{\sum_{ij} E_{ij}^2}{Y_{rms}^2} - \frac{\sum_{ij} E_{ij}^2}{X_{rms}^2}} \right)
\]

\[
M = \sum_{ij} E_{ij} \times (X_{rms} \cos^2 \phi + Y_{rms} \sin^2 \phi + 2 \langle XY \rangle_{rms} \cos \phi \sin \phi)
\]
Modulation Factor

- Fit function to the angular distribution
  \[ N(\phi) = A + B \cos^2(\phi + \phi_{pol}) \]

- Polarisation Sensitivity or Modulation Factor, \( \mu \):
  \[ \mu = \frac{N_{\text{max}} - N_{\text{min}}}{N_{\text{max}} + N_{\text{min}}} = \frac{B}{2A + B} \]
Small Pixel CCD Polarimeters
Micro-Pattern Gas Polarimeter

- X-ray interacts in the gas
- Photoelectron creates electron cloud
- Electron cloud drifts to cathode
- Electron multiplication occurs between cathode and anode
- Charge finally collected at the pixel readout
Initial Results

Track images in Neon:
- 6 keV
- 4.5 keV

At 4.5 keV $\mu=30\%$

Histograms of emission angles from reconstructed 4.5 keV events

(Black et al. 2001)
Further Development

- Based on this promising result continued development to build a flight prototype
- Improve on the previous measurements by using an ASIC with hex pixels for the readout

\[ FOM = QE^{-1/2} \Delta E^{-1/2} \mu^{-1} \]

<table>
<thead>
<tr>
<th>Type of Polarimeter</th>
<th>Modulation Factor (%)</th>
<th>Quantum Efficiency (%)</th>
<th>Characteristic Bandwidth (keV)</th>
<th>Figure of Merit</th>
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<tbody>
<tr>
<td>Bragg Crystal Thomson Polarimeters</td>
<td>96</td>
<td>99</td>
<td>0.22</td>
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<td>OSO-8</td>
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<td>30</td>
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<td>SXRP</td>
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<td>CCD Polarimeter</td>
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<tr>
<td>12 x 12 µm (exp)</td>
<td>3</td>
<td>3</td>
<td>25</td>
<td>38</td>
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<tr>
<td>4 x 4 µm (mod)</td>
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<td>3</td>
<td>25</td>
<td>7.2</td>
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<td>4 x 9 µm (exp)</td>
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<td>41</td>
<td>12.5</td>
<td>2.4</td>
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<tr>
<td>0.5 x 0.5 µm (mod)</td>
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<td>50</td>
<td>15</td>
<td>2.2</td>
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<td>Micro-pattern gas</td>
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<td></td>
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<tr>
<td>Proportional Counter</td>
<td>30</td>
<td>30</td>
<td>4</td>
<td>3.0</td>
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</tbody>
</table>
The proto-type set-up
Readout Electronics

- An FPGA controls the ASIC and the ADC
- Allows a programmable window mode - preserves telemetry
- Real-time pedestal subtraction (bias subtraction)
- Event-by-event centroid calculation
Detector set-up

Drift Electrode

Cathode & Anode

ASIC
Detector Optimisation

- 150 μm meshes: 120 μm separation
- 200 Torr of CO₂
- Anode 1 mm from Cu collector
Detector Optimisation

- 150 μm meshes: 180 μm separation
- 200 Torr of CO₂
- Anode 1 mm from Cu collector
Mesh Configuration

- Decreasing spacing yields greater throughput to collector
- Spacing too narrow => HV breakdown in the multiplication region at low gain
- 150 \( \mu \)m separation is \( \sim \) optimum

Cathode \(^{55}\)Fe Spectrum \( \Delta E/E=\sim22\% \)
Preliminary ASIC Tests

- 80 μm pitch ASIC (building 50 μm pitch)
- Substitute ASIC in place of Cu plate
- 150 μm pitch meshes at 180 μm separation

Un-polarised $^{55}$Fe X-rays
355 Torr of CO$_2$
Drift 1.84 kV
Cathode 1.48 kV
Anode 500 V
ASIC Vdd=2.82 V
(Very) Preliminary Results

- Optimising the event analysis software
- Discard edge events
- Discard low energy events
- Tests with unpolarised $^{55}$Fe, 0 degrees and 320 degree polarised Titanium X-rays
Further Work

- Determine modulation factor for current configuration
- Verify results against the simulator
- For a given energy band
  - Characterise different gases
  - Optimise pressure
- Optimise voltages for resolution and sensitivity
- Test meshes with 80 μm pitch
- Characterise ASIC operation
- Quantify Quantum Efficiency for optimum polarization sensitivity
Future Plans

- Operate detector at mirror focus
- Secure a funding opportunity to prove the concept
  - Sounding Rocket: 15 mins, 0.6-6 keV
  - Balloon: 20 hrs, 30-50 keV
  - SMEX or MIDEX
Polarimetry Group

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