Using Multilayer Optics to Measure X-ray Polarization

Herman L. Marshall (MIT CSR)
and E. Silver, H. Schnopper, S. Murray (SAO),
M. Weisskopf (MSFC)
Background: an Attempt to Measure EUV Polarization - I

- Used Extreme Ultraviolet Explorer (EUVE)
- Deep Survey telescope graze angles were 5-10°, so reflectivity is polarization-sensitive
- DS focal surface is not planar, so off-axis images have shape of aperture
- Predicted modulation factor: 4%
- Observed PKS 2155-304 for 200,000 s, getting 100,000 events
Background: an Attempt to Measure EUV Polarization - 2

• The BL Lac image differs from the WD image
  • Differences are not due to polarized flux
  • Uncalibrated systematic errors dominate

• Motivation to design experiment for soft X-ray polarimetry

Marshall et al. 2001
A Soft X-ray Polarimeter

- Designed as a polarimeter from outset
  - Mirror angle of incidence centered at 45°
  - Use multilayer coatings to improve reflectivity in X-ray band
  - Chose 250 eV to use common successful multilayer combinations
    - ISM optical depth < 1 for $N_H < 3 \times 10^{20}\text{cm}^{-2}$
    - Maximizes photon flux: $R \propto \delta E n_E \propto f E^{-\Gamma+1}$
  - 3rd generation: image portions of a 3 mirrors using 3 detectors

- Scientific goals
  - Measure AGN polarizations to ± 1% — drives bandpass, area
  - Determine PSR polarization variation with pulse phase — drives timing
  - Observe 50-200 targets in 1-3 yr — drives area

- Proposed as University Explorer (UNEX)
  - Cost cap was $13M, including launch
  - Proposed (then) free Shuttle launch with Spartan carrier
  - Awarded technology development funding
Multilayer Physics

- Multilayer coatings are crude crystals
- Bragg equation gives bandpass peak: \( \lambda = 2d \cos \theta \)
  - \( d \) is multilayer spacing (2 or more layers)
  - \( \theta \) is angle of incidence
- Interface roughness (2-5 Å) is important
  - Reflectivities are well modelled
  - Feasible peak energy limited to < 1 keV

Figures from Dave Windt’s website
Multilayer Measurements

- Excellent multilayers have been deposited
- Models of reflectivities match observations

<table>
<thead>
<tr>
<th>Material</th>
<th>d (Å)</th>
<th>N</th>
<th>Angle</th>
<th>E</th>
<th>R</th>
<th>dE</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni/C</td>
<td>48</td>
<td>20</td>
<td>45°</td>
<td>180 eV</td>
<td>18%</td>
<td>9 eV</td>
<td>Yamamoto</td>
</tr>
<tr>
<td>Mo/B4C</td>
<td>49</td>
<td>100</td>
<td>45°</td>
<td>185 eV</td>
<td>23%</td>
<td>2 eV</td>
<td>Yamamoto</td>
</tr>
<tr>
<td>Ru/B4C</td>
<td>49</td>
<td>100</td>
<td>43°</td>
<td>185 eV</td>
<td>19%</td>
<td>2 eV</td>
<td>Yamamoto</td>
</tr>
<tr>
<td>Ni/C</td>
<td>31.6</td>
<td>75</td>
<td>45°</td>
<td>277 eV</td>
<td>10%</td>
<td>4 eV</td>
<td>Dietsch</td>
</tr>
<tr>
<td>Co/C</td>
<td>30</td>
<td>41</td>
<td>47°</td>
<td>282 eV</td>
<td>12%</td>
<td>7 eV</td>
<td>Grimmer</td>
</tr>
<tr>
<td>Ni/Ti</td>
<td>20</td>
<td>75</td>
<td>42°</td>
<td>451 eV</td>
<td>5.9%</td>
<td>3 eV</td>
<td>Grimmer</td>
</tr>
<tr>
<td>Ni/V</td>
<td>17</td>
<td>150</td>
<td>44°</td>
<td>510 eV</td>
<td>6.8%</td>
<td>3 eV</td>
<td>Grimmer</td>
</tr>
<tr>
<td>Cr/Sc</td>
<td>16</td>
<td>300</td>
<td>2.5°</td>
<td>390 eV</td>
<td>6.9%</td>
<td>1.2 eV</td>
<td>Windt</td>
</tr>
<tr>
<td>W/B4C</td>
<td>18.</td>
<td>300</td>
<td>2.5°</td>
<td>690 eV</td>
<td>0.25%</td>
<td>0.3 eV</td>
<td>Windt</td>
</tr>
</tbody>
</table>

From CXRO web site, Windt et al.
• Mirrors are paraboloidal sectors
  • One bounce system improves reflectivity
• 45° mirror reflection angles
  • Maximizes modulation factor
  • Instrument is compact

Detectors are simple, need only 0.1 mm spatial and no spectral resolution
Optics Layout — 2

- **Mirror assemblies divided into 4 x 10° segments**
  - Each assembly has a dedicated detector
  - Mirror/detector combinations are optically identical, $F = 0.33$ m

- **Mirror segments are imaged independently**
  - Polarization modulation improves from 70% to 90%
  - Robust to pointing direction
  - Internal background is low, comparable to diffuse X-ray background
Detailed Multilayer Design

- Use C/Ni Multilayer
  - Spacing (d) is 30-40 Å
  - dC/d = 0.6
  - Modulation factor ≠ f(E)
  - Interfaces are stable
  - C/W and C/Co are also OK

- Include Interface Roughness of 5 Å
  - ML coatings from SAO facility are this good
  - Peak reflectivity decreases x2 from no roughness case
• Final bandpass includes other effects
  • ML spacing changes along mirror surface based on sputterer distance
  • Lexan/Al filter blocks UV and optical light

• High orders are negligible
• Interfaces are simple
• Star tracker added for better attitude reconstruction
• Redundant telescopes
• 3 Stokes parameters can be measured at once
• Rotate to remove systematic effects
## Sample 90\textsuperscript{d} Observing Plan

<table>
<thead>
<tr>
<th>Category</th>
<th>Example</th>
<th>Cnt Rate (cnt/s)</th>
<th>Exposure (day)</th>
<th>Meas. uncert. (%)</th>
<th>MDP (%)</th>
<th># visits (in 3 mon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsar</td>
<td>Her X-1</td>
<td>0.65</td>
<td>0.5</td>
<td>1.21</td>
<td>6.1</td>
<td>4</td>
</tr>
<tr>
<td>Pulsar</td>
<td>Vela</td>
<td>0.1</td>
<td>5</td>
<td>0.98</td>
<td>4.9</td>
<td>1</td>
</tr>
<tr>
<td>BL Lac</td>
<td>PKS 2155-30</td>
<td>1.3</td>
<td>0.5</td>
<td>0.86</td>
<td>4.3</td>
<td>6</td>
</tr>
<tr>
<td>BL Lac</td>
<td>Mkn 421</td>
<td>0.8</td>
<td>0.5</td>
<td>1.09</td>
<td>5.5</td>
<td>6</td>
</tr>
<tr>
<td>BL Lac</td>
<td>Mkn 501</td>
<td>0.11</td>
<td>1</td>
<td>2.08</td>
<td>10.4</td>
<td>3</td>
</tr>
<tr>
<td>BL Lac</td>
<td>1H1023</td>
<td>0.14</td>
<td>1</td>
<td>1.84</td>
<td>9.2</td>
<td>3</td>
</tr>
<tr>
<td>AGN/Quasar</td>
<td>Mk 478</td>
<td>0.25</td>
<td>1.5</td>
<td>1.13</td>
<td>5.6</td>
<td>4</td>
</tr>
<tr>
<td>AGN/Quasar</td>
<td>3C 273</td>
<td>0.2</td>
<td>2</td>
<td>1.09</td>
<td>5.5</td>
<td>10</td>
</tr>
<tr>
<td>AGN/Quasar</td>
<td>NGC 5548</td>
<td>0.14</td>
<td>3</td>
<td>1.06</td>
<td>5.3</td>
<td>10</td>
</tr>
<tr>
<td>AGN/Quasar</td>
<td>1H0419-577</td>
<td>0.17</td>
<td>3</td>
<td>0.97</td>
<td>4.8</td>
<td>3</td>
</tr>
<tr>
<td>WD</td>
<td>HZ 43</td>
<td>3.5</td>
<td>0.3</td>
<td>0.67</td>
<td>3.4</td>
<td>3</td>
</tr>
<tr>
<td>WD</td>
<td>WD 1502</td>
<td>0.9</td>
<td>0.7</td>
<td>0.87</td>
<td>4.3</td>
<td>3</td>
</tr>
<tr>
<td>WD</td>
<td>Sirius</td>
<td>0.63</td>
<td>1</td>
<td>0.87</td>
<td>4.3</td>
<td>3</td>
</tr>
</tbody>
</table>
Science Goals (abridged)

- **Quasars**: discriminate between jets and disks in quasar core
- **Pulsars**: determine pulsar B-field geometry, model NS radius with better atmospheres

(Pavlov & Zavlin 2000)
X-rays from Radio Jets

Radio Evolution of Sco X-1

1-1999 Jun 11 at 02:47

Invisible Receding Lobe

Advancing Lobe

Sco X-1 Binary System

Billion Miles

SS433

VLBA

Amy Mioduszewski
Michael Rupen
Craig Walker
Greg Taylor

VLBA tracks jets

Development Status

- Polarization source built at SAO
  - Output is nearly 100% polarized
  - PLEXAS concept is validated in principle

- UNEX program is gone
  - Add as Mission of Opportunity?
  - Attach to Space Station?

Emily Laubacher (SAO summer intern) works on the polarization source.
Summary

• A Polarimeter for Low Energy Astrophysical Sources (PLEXAS) is feasible
  • Simple design, low cost and weight
  • Technology is robust and proven to work

• Science potential is wide-ranging
  • Test models of BL Lac jets
  • Test origin of X-rays from quasar cores
    • Discover pc-scale jets in quasar cores
    • Test for rotation of polarization around quasar black holes
  • Measure propagation of light in high B and high g
    • Improve models of neutron stars atmospheres
    • Radius estimates and equation of state depends on atmosphere models

• Looking for (NASA?) development program — good match for 2-20 keV polarimeters