Future prospects for solar flare \textit{(but not only)} X-ray polarimetric missions

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On the behalf of the
High Energy Astrophysics and Related Technology Group
at the
INAF – IAPS (Rome)

5-8 May 2014, Prague
OUTLINE

- X-ray polarimetry as a diagnostics for solar flares
- Photoelectric polarimetry with the Gas Pixel Detector (GPD)
- Mission proposals and collaborations
- More to come: Compton polarimetry
SOLA FLARES X-RAY POLARIMETRY

Emission lines $< 10$ keV [Doschek 2002]

Thermal bremsstrahlung up to 20 keV
(possibly low polarized if Maxwellian distribution of velocity is perturbed by plasma expansion along magnetic field lines due to heat propagation)
[Emslie & Brown 1980]

Non-thermal bremsstrahlung $>20$ keV
(highly polarized up to 40%)
[Zharkova et al. 2010]

Moreover:
Scattering of radiation... therefore still polarization
PRESENT RESULTS

Fig. 10. Comparison of the simulations of HXR bremsstrahlung polarization for 20 keV (left plot) and 200 keV (right plot) produced for different position angle on the solar disk ($\cos \Xi = 1$ in the disk center and 0 on the limb) by a wider electron beam with $\Delta \mu = 0.2$ and the energy flux of $10^{10}$ erg cm$^{-2}$ s$^{-1}$ ($\gamma = 3$: C+E model – solid line, C+E+B model – solid line with crosses; $\gamma = 7$: C+E model – dashed line, C+E+B model – dashed line with crosses) and by more collimated ($\Delta \mu = 0.02$) electron beam (C+E model) with $\gamma = 7$ and the initial energy fluxes of $10^{10}$ (dot-dashed lines) and $10^{12}$ erg cm$^{-2}$ s$^{-1}$ (dotted lines). The observation results are plotted as follows: diamonds correspond to the observations of Tindo et al. (1970, 1972a,b) at 15 keV, triangles – to the observations of Tramiel et al. (1984) at 16-21 keV, squares – to the observations of Suarez-Garcia et al. (2006) at 100–350 keV, and asterisks – to the observations of Boggs et al. (2006) at 200–400 keV.

Models
C = particle collisions
E = beam electron self induced electric field (Zharkova et al. 2010)
B= magnetic field convergence
Solar flare polarimetry… What do we need?

Soft X-rays (high flux, contamination by thermal emission):

Photoelectric polarimetry (high efficiency in SXRs)

Hard X-rays (low flux, only non-thermal emission):

Compton polarimetry (high efficiency in HXRs)
[Fabiani et. al. 2012, Jour.of Phys. Conf. Ser.]

Nice to have:
Imaging capability with angular resolution (<= 10 arcseconds) to separate solar flare emitting regions (footpoints and looptop) and perform imaging-polarimetry
POLARIMETRY BASICS

Polarimeter = Analyser + Detector

Analyser: For analysing different angles of polarization

Detector: To detect photons for each angle

Unpolarized radiation → flat response

Polarized radiation → Modulated response

\[ N(\phi) = A_P + B_P \cos^2(\phi - \phi_0) \]

MODULATION FACTOR (measured with 100% pol. rad.)
Polarization Degree

\[ \mathcal{P} = \frac{1}{\mu} \frac{B_p}{2A_p + B_p} \]

Minimum Detectable Polarization (at 99% confidence level)
[Weisskopf et al. 2010]

\[ \text{MDP} = \frac{4.29}{\mu \cdot R} \cdot \sqrt{\frac{R + B}{T}} \]

R : source rate
B : background rate
T : integration time
POLARIMETRY BASICS

\[ I = \frac{1}{2\pi} \int_0^{2\pi} N(\phi), d\phi = A_P + \frac{B_P}{2} \]

\[ Q = \frac{1}{\mu} \frac{B_P}{2} \cos 2\phi_0 \]

\[ U = \frac{1}{\mu} \frac{B_P}{2} \sin 2\phi_0 \]

\[ P = \frac{\sqrt{Q^2 + U^2}}{I} = \frac{1}{\mu} \frac{\sqrt{\frac{B_P^2}{4} \cos^2 \phi_0 + \frac{B_P^2}{4} \sin^2 \phi_0}}{A_P + \frac{B_P}{2}} = \frac{1}{\mu} \frac{B_P}{2A_P + B_P} \]
PHOTOELECTRIC POLARIMETRY: the GPD

Cross section K-shell

\[
\frac{d\sigma_K}{d\Omega} \propto \frac{3 \sin^2 \theta \cos^2 \phi}{(1 - \beta \cos \theta)^4} \propto \cos^2 \phi
\]

\(\Phi\): Azimuthal angle of emission of the photoelectron

GPD

Lab BEE
PHOTOELECTRIC POLARIMETRY: the GPD

1. **Polarimetry:**

   degree and angle

2. **Moderate spectroscopy:**

   20% at 6 keV

3. **Imaging:**

   impact point detection

   (LEP: Spatial Resolution FWHM 70mm, measured by Soffitta et al. 2012, NIMA)

4. **Timing:**

   photon by photon detection (some us)

---

**Low Energy Polarimeter (LEP) 2-10 keV:**

- He based gas mixtures

**Medium Energy Polarimeter (MEP) 6-35keV:**

- Ar based gas mixtures

- Good for solar flares polarimetry,
  [Fabiani et al. 2012, SPIE]
PHOTOELECTRIC POLARIMETRY: the GPD

To derive the image of the source the detector must be coupled with:

- Grazing incidence X-ray telescope
- Coded mask aperture
- Rotating modulation collimator

If no imaging is required:

- Collimator
- Field angular delimiter
MISSION PROPOSAL: 2012 ESA call for a small mission
X-ray Imaging Polarimeter Explorer (XIPE)

2 LEP 20%He-80%DME coupled to 2 optics module of JET-X telescope (HEW 15arcsec @ 1.5 keV) for non-solar sources. Energy band 2-10 keV (MDP 14% in 100ks for 1mCrab)

2 MEP 60%Ar-40%DME with a field angular delimiter for solar flares observations (Energy band 15-35keV)

SPHINX – photometer for solar observations 1.2-15 keV (recurrent from CORONAS-P mission) [SRC-PAS Wrocław (Poland)]
MISSION PROPOSAL: 2012 ESA call for a small mission
X-ray Imaging Polarimeter Explorer (XIPE)

XIPE Solar Polarimeter sensitivity

<table>
<thead>
<tr>
<th>Flare Class</th>
<th>MDP (%)</th>
<th>Integration Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X10</td>
<td>0.6</td>
<td>748</td>
</tr>
<tr>
<td>X5.1</td>
<td>1.3</td>
<td>989</td>
</tr>
<tr>
<td>X1.2</td>
<td>4.8</td>
<td>239</td>
</tr>
<tr>
<td>M5.2</td>
<td>6.6</td>
<td>489</td>
</tr>
<tr>
<td>M1</td>
<td>46.4</td>
<td>128</td>
</tr>
</tbody>
</table>

Spectra from Saint-Hilaire et al. 2008
TWO MISSION PROPOSALS: 2012 ESA call for a small mission X-ray Imaging Polarimeter Explorer (XIPE)

BHs: Polarization angle rotation with energy

Fig. 6 (a). Expected variation of the polarization degree with energy in GRS1915+105 simulating an observation of 300 ksec The model is from Dovčiak et al (2008) while the errors are evaluated for the case of an observation with XIPE). (b). Polarization angle rotation with energy in the same observation.

Calibrations at PANTER (27 Nov-1 Dec 2012)

X-RAY SOURCE

100 m BEAM LINE

VACUUM CHAMBER

CONTROL ROOM

GPD

ROSAT PSPC

eROSETA TRoPIC CCD

JET-X Flight Module

VACUUM CHAMBER

PSF measurement of GPD+telescope optics

At present angular resolution is limited by optics, not by the detector

Crab Pulsar Wind Nebula

Table 4

<table>
<thead>
<tr>
<th>Region No.</th>
<th>( \sigma_{\text{degree}} ) (%)</th>
<th>( \sigma_{\text{angle}} ) (deg)</th>
<th>MDP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.7</td>
<td>1.1</td>
<td>2.2</td>
</tr>
<tr>
<td>2</td>
<td>0.5</td>
<td>0.8</td>
<td>1.5</td>
</tr>
<tr>
<td>3</td>
<td>0.8</td>
<td>1.3</td>
<td>2.5</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
<td>1.6</td>
<td>3.2</td>
</tr>
<tr>
<td>5</td>
<td>0.7</td>
<td>1.1</td>
<td>2.2</td>
</tr>
<tr>
<td>6</td>
<td>0.5</td>
<td>0.9</td>
<td>1.7</td>
</tr>
<tr>
<td>7</td>
<td>0.5</td>
<td>0.8</td>
<td>1.6</td>
</tr>
<tr>
<td>8</td>
<td>0.5</td>
<td>0.8</td>
<td>1.6</td>
</tr>
<tr>
<td>9</td>
<td>0.5</td>
<td>0.9</td>
<td>1.7</td>
</tr>
<tr>
<td>10</td>
<td>0.7</td>
<td>1.1</td>
<td>2.2</td>
</tr>
<tr>
<td>11</td>
<td>0.6</td>
<td>1.0</td>
<td>1.9</td>
</tr>
<tr>
<td>12</td>
<td>0.6</td>
<td>1.0</td>
<td>1.9</td>
</tr>
<tr>
<td>13</td>
<td>0.7</td>
<td>1.1</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Notes. The source is subdivided in 13 regions as shown in Figure 11 (bottom panel). The uncertainties of the degree and angle of polarization are listed, assuming a polarization degree of 19% (Weisskopf et al. 1978) in the energy range 2–10 keV for a 100 ks observation.
FUTURE PROSPECTS FOR X-RAY POLARIMETRY:

• **ESA-CAS proposals:**
  - **XIILPE: A Light** (=descooped) version of XIPE:
    - No solar polarimeters. One telescope only.
    - JET-X optics will be reproduced with modern technology (a lighter optics module, possibly larger effective area)
  - **SEELPE (Solar Energetic Emission and Particle Explorer):**
    - High Energy Band Spectrometer (HEBS) (10 keV- 600 MeV)
    - Solar X-ray Polarimeter (15-35 keV)
    - Electron-Proton and High-Energy Telescopes (EPT-HET)
    - Supra-Thermal Electrons & Protons (STEP)

• **Next NASA SMEX call:**
  - X-ray Polarimetry dedicated mission with GPD (no solar polarimeter)
    - Weisskopf et al. 2013, SPIE

• **Next ESA Cubesat call:**
  - nano-satellite composed by 3 cubes 10 cm of side (!!)
  - 1 solar GPD (IAPS, INFN-Pisa, Univ. of Rome «Tor Vergata»),
  - X-ray solar photometer (SRC-PAS in Wrocław, Univ. of Wrocław (Poland))
MOVING TOWARDS COMPTON POLARIMETRY: polarimeter concept

\[ \frac{d\sigma}{d\Omega} \sim \frac{r_0^2}{2} \frac{E'^2}{E^2} \left[ \frac{E}{E'} + \frac{E'}{E} - 2 \sin^2 \theta \cos^2 \phi \right] \]

Focal plane configuration

Fabiani et al. 2013, Astroparticle Physics

Non Focal plane configuration

MDP=4.2% for M5.2 class flare (spectra by Saint-Hilaire et al. 2008)

MDP=10% for 10mCrab in 100ks @ 1 NuStar optics module (3 cm scatterer length tested in lab but not optimized)

Costa et al. 1995
CONCLUSIONS

• Precise polarimetry in X-rays is now feasible

• Solar flare X-ray polarimetry would allow to drive plasma and magnetic field properties in solar atmosphere, contributing to present studies

• A wide population of astrophysical sources characterized by polarized mission are suitable to be observed:
  ➢ See the paper about XIPE by Soffitta et al. 2013, Experimental Astronomy, Vol.36, pp.523 «XIPE: the X-ray imaging polarimetry explorer» for an updated review about science targets of photoelectric polarimetry

AND...
Thanks to COST Action MP1104 that funded the STSMs of

- Sergio Fabiani and Fabio Muleri to join the calibration of the GPD at the PANTER X-ray test facility (Germany) in 2012

- Sergio Fabiani to visit the Solar Physics Division of the Polish Accademy of Science in Wrocław (Poland) to start a collaboration for future proposals about solar flare X-ray polarimetry missions (Cubesat) in 2013
Table 5

<table>
<thead>
<tr>
<th>Region No.</th>
<th>$\sigma_{\text{degree}}$ (%)</th>
<th>$\sigma_{\text{angle}}$ (deg)</th>
<th>MDP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.4</td>
<td>6.6</td>
<td>7.7</td>
</tr>
<tr>
<td>2</td>
<td>2.7</td>
<td>8.3</td>
<td>8.8</td>
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<tr>
<td>3</td>
<td>2.1</td>
<td>5.9</td>
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</tr>
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<td>3.5</td>
<td>11.0</td>
<td>11.1</td>
</tr>
<tr>
<td>7</td>
<td>3.6</td>
<td>11.0</td>
<td>11.6</td>
</tr>
</tbody>
</table>

Notes. The source is subdivided in 7 regions as shown in Figure 12 (bottom panel). The uncertainties of the degree and angle of polarization are listed, assuming a polarization degree of $11\%$ in the energy range $4-6$ keV for a $2$ Ms observation. Regions 4, 6, and 7 are probably dominated by the non-thermal component, therefore the polarization arising from their emission should be higher with respect to regions 1, 2, 3, and 5 in which the thermal component is dominant.

Calibrations at PANTER (27 Nov-1 Dec 2012)


Figure 10. Off-axis HEW at 2.98, 4.51, and 8.05 keV. Plotted values are listed in Table 3. The FOV of JET-X coupled with the GPD (see Table 1) corresponds to an angle of 10.4 arcmin from the image center to the corner along the diagonal.
Polarimeter geometry is based on the laboratory set-up (3cm scint. rod) that is not optimized for polarimetric observations, but... MDP=10% for 10mCrab in 100ks !!

[1Crab in 20-80keV is 1.5*10^{-8} erg cm^{-2} s^{-1}]
What is a cubesat?
- Very small satellite composed typically by 1, 2 or 3 units
- Each unit is a cube 10 cm of side (gross dimension !!)
- Payload max : 1 Kg each unit
- Power : about 1W each face
- Costs: of the order of 1MEuro

Typical Cubesat Goals
- Mechanical and electronics testing
- University educational programs in collaboration with space agencies

Our Target
ESA call for Cubesats (educational program) next call on the beginning of 2014

Involved Institution
INAF-IAPS in Rome (Italy) [Polarimeter]
INFN Section of Pisa (Italy) [Polarimeter]
SRC-PAS in Wrocław (Poland) [Photometer]
Univ. of Wrocław (Poland) [Photometer]
Univ. of Rome «Tor Vergata» (Italy) [bus services]
## FUTURE PROSPECTS FOR X-RAY POLARIMETRY:
### A CUBESAT FOR SOLAR FLARE POLARIMETRY

### 3 Units Cubesat

<table>
<thead>
<tr>
<th>Polarisimetry</th>
<th>Spectro/Photometry</th>
<th>Bus Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Flare Polarimeter (GPD - MEP) 15-35 keV</td>
<td>Solar Photometer (SPHINX upgrade: Si, CdTe)</td>
<td>Pointing control</td>
</tr>
</tbody>
</table>

**Instrumental team**
- INFN Sezione di Pisa
- INAF-IAPS
- AMDL (GPD fast electronics)

**Theory and modeling**
- Univ. of Northumbia (UK) (Prof. Valentina Zharkova)

**Instrumental and theory**
- SRC-PAS Wroclaw (Poland)
- Univ. of Wroclaw (Poland)
- Lebedev Inst. of Moskow (Russia) [possibly]

...and for all you need go on...

**Bus Services**
- Univ. of Rome “Tor Vergata”
- Telemetry, Mass memory, Power distribution, etc.

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CubeSatShop.com
The one-stop-shop for all your CubeSat and nanosat systems...
THE POLARIMETRIC PAYLOAD LAYOUT

1 GPD (MEP): Ar70%, DME30%,
3 atm, 3 cm, 2.25 cm^2
15-35 keV

Height (boards+GPD+HV)  7.4 cm
Total Weight           500 g
Total Power           2 W

Flare Class   Avg. Rate (c/s) | Int. Time (s) | MDP (%)
---------------|----------------|----------
X10           1348             | 749         | 1
X5.1          203              | 989         | 2
X1.2          63               | 240         | 7
M5.2          17               | 489         | 9

MDP evaluated from spectra in web additional material of Saint-Hilaire et al. 2008

About 1-2 flares per month between class M5 and X10 in 2016
Visible – NIR payload:
Observations of the solar photosphere and chromosphere at high-temporal rate and high spatial and spectral resolutions.
→ 50cm Gregorian type telescope
→ Fabry-Pérot interferometer with piezoelectric actuators to match cavity length with radiation wavelength.

X-ray payload:
4 MEP, 1 coupled with a coded mask aperture to allow the flare localization onto the solar disc, 3 coupled with a field angular delimiter.

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<td>35.5</td>
<td>128</td>
</tr>
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Spectra from Saint-Hilaire et al. 2008
PRESENT RESULTS

Small Effective Area and high signal threshold:

→ **RHESSI** (spectrometer, Compton scattering among Ge rods to try to measure polarization).
  Summary of results by Suarez-Garcia et al. 2006
  → Compton events in the photoelectric/Compton cross-section transition (Energy range 100-350 keV)
  → High probability to scatter X-ray photons out of the detector active region

<table>
<thead>
<tr>
<th>Flare number</th>
<th>Date</th>
<th>phi (deg)</th>
<th>Pi (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(RHESSI)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2072301</td>
<td>July 23, 2002</td>
<td>151 ± 195</td>
<td>2 ± 14</td>
</tr>
<tr>
<td>3110221</td>
<td>November 2, 2003</td>
<td>96 ± 12</td>
<td>28 ± 12</td>
</tr>
<tr>
<td>4111002</td>
<td>November 10, 2004</td>
<td>104 ± 24</td>
<td>36 ± 26</td>
</tr>
<tr>
<td>5011710</td>
<td>January 17, 2005</td>
<td>71 ± 29</td>
<td>28 ± 25</td>
</tr>
<tr>
<td>5011911</td>
<td>January 19, 2005</td>
<td>170 ± 11</td>
<td>54 ± 21</td>
</tr>
<tr>
<td>5012005</td>
<td>January 20, 2005</td>
<td>66 ± 14</td>
<td>21 ± 10</td>
</tr>
<tr>
<td>5082502</td>
<td>August 25, 2005</td>
<td>102 ± 104</td>
<td>6 ± 25</td>
</tr>
</tbody>
</table>

. Pi is the polarization degree of the flare, and phi its polarization angle given in heliocentric coordinates.

Signal dominated by background:

→ **SPR-N** on board CORONAS-F (Thomson scattering polarimeter), Zhitnick et al. 2006
→ Energy range 20-100 keV
→ Large geometric area (50 cm^2) scatterer, small effective area
→ Passive scatterer, no background reduction. Signal dominated by background.
→ Signal heavily affected by radiation background especially when passing near the poles (h=500 km, incl. 82.5°)
MONTHLY FLARE RATE

<table>
<thead>
<tr>
<th>Classes</th>
<th>Flux (peak) 0.1-0.8 nm [W/m^2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$10^{-8}$-$10^{-7}$</td>
</tr>
<tr>
<td>B</td>
<td>$10^{-7}$-$10^{-6}$</td>
</tr>
<tr>
<td>C</td>
<td>$10^{-6}$-$10^{-5}$</td>
</tr>
<tr>
<td>M</td>
<td>$10^{-5}$-$10^{-4}$</td>
</tr>
<tr>
<td>X</td>
<td>$&gt;10^{-4}$</td>
</tr>
</tbody>
</table>

- 338661 all flares
- 35221 C-class flares
- 3986 M-class flares
- 248 X-class flares

Logarithmic monthly flare rate against time [years] from 1980 to 2010.
SOLAR FLARES X-RAY EMISSION
- Magnetic reconnection
- Acceleration of particles
  (lower atmosphere and solar wind)
- Plasma heating

X-RAY POLARIZATION
- Non-thermal Bremsstrahlung polarized emission,
- Local magnetic field geometry,
- Active regions environment