Solar Energetic Emission and Particles Explorer (SEEPE)

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Scientific Motivation

Solar Magnetic Fields

Magnetic Reconnection

Flare, CME, Solar Wind

Space Weather
Observations of energetic emission in solar flares $\rightarrow$ relativistic particles

- Magnetic reconnection is a fundamental process of energy release in solar flares
- This process can account for generation of relativistic particles with power law energy distributions
- This process ejects highly directed particles along magnetic field direction

Large numbers of non-thermal ions and electrons produced in flares


Scientific Motivation

Energy Release

- Acceleration
- Heating
- Turbulence and Waves
- Radiations (non-thermal)
- Radiations (non-thermal)
- IMPULSIVE
- IMPULSIVE

- Transport
- Heating
- Heating
- Heating
- Acceleration
- Radiations (non-thermal)

- Emission (thermal)
- GRADUAL
PARTICLE PRECIPITATION

Zharkova et al. (2010) using Fokker-Plank equation for the evolution of electron distribution and using bremsstrahlung cross-section tackled the problem of deriving Hard X-ray spectrum, directivity and polarization of solar flares.

Taking into account:
1. **Collision loss**
2. **Self-induced electric field** (Ohmic losses)
3. **Converging magnetic field** (loss cone)

Returning electrons are present (negative cosine) mostly due to (2) and (3) effects (see cartoon).
Evolution of the directivity and polarization degree at 30 keV and 100 keV for soft \((\gamma = 7)\) and hard \((\gamma = 3)\) electron beam for different pitch (emission) angle of photons.

- Intensity is mostly directed down-ward for hard electron spectrum while it evolves upward for soft electron spectrum due to return current.
- Polarization is highest for \(\varphi = 90^\circ\) it decreases at large depth due to randomization.
- Not shown but the evolution with depth of polarization and directivity depends on the model of precipitation assumed.
**Intensity** and polarization spectrum of the whole flare for soft and hard electron beam.

**Solid**: Collision; **dotted** collision and return current; **Dashed**: Collision and converging magnetic beam **Dash-dotted**: all

- Energy dependent polarization measurement helps to disentangle between precipitation models and electron beam hardness.
- Energy breaks in the intensity spectrum helps to further constrain beam hardness.
- Maximum of polarization is reached at low energy for soft beam and when the flare is on the limb $\vartheta = 90^\circ$. 

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Siming Liu (PMO) Paolo Soffitta (IAPS)
Current observational status and direction for an ESA-CAS small mission.


However:

- Present measurements have low significance mostly due to the sensitivity and threshold of the instruments flown up-to now. Much more precision for measurements across the whole sun disk are needed to constrain models and to determine the plasma parameters.
- Measurements resolved in energy are very desirable. The energy band 15-35 keV looks promising because of the larger polarization and flux expected.
- Time resolved polarimetry finally would allow to study the evolution. However, the necessary time resolution may be in contrast with the large number of counts needed for a sensitive measurement placing constraints on the collecting area needed.
Scientific Motivation

Low-energy: Gradual Thermal Coronal Source

High-Energy: Impulsive Non-thermal Chromospheric Footpoints

Scientific Aim

To explore the magnetic energy release and consequent plasma heating and particle acceleration in the solar atmosphere by distinguishing the thermal and the non-thermal emission component:

<table>
<thead>
<tr>
<th>Thermal</th>
<th>Non-thermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temporal</td>
<td>Gradual</td>
</tr>
<tr>
<td>Spectral</td>
<td>Exponential</td>
</tr>
<tr>
<td>Polarization</td>
<td>Isotropic</td>
</tr>
<tr>
<td>Transport</td>
<td>Local</td>
</tr>
</tbody>
</table>
High Energy Burst Spectrometer (HEBS)

Size: $362 \times 349 \times 172.5 \text{mm}$
Weight: 20.5 kg
Power: 20 W
Energy Range: 10keV - 600MeV
Energy Resolution: 3%@662keV
Temporal Resolution: 1s (quiescent), 32ms (flare-mode)

It is a possible GRB detector (area = 0.55 of Fermi GBM/BGO)
Scientific Payload

X-ray Polarimeter (Polarization)

- Weight: 16 kg
- Power: 25 W
- Energy Range: 10-35keV (for non-thermal bremsstrahlung)

A solar flares X-ray polarimeter

S. Fabiani\(^1\), R. Bellazzini\(^2\), F. Berrelli\(^3\), A. Brez\(^4\), E. Costa\(^1\), F. Muleri\(^1\), M. Pinchera\(^2\), A. Rubini\(^1\), P. Soffitta\(^1\), and G. Spandre\(^2\)

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

<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>

GAS PIXEL DETECTOR (GPD)

LAB. BEE
Every polarimeter is composed of (1) an analyzer, a stage where an interaction occurs, whose outcome angle depends on polarization, and (2) a detector of the products of the interaction, capable to measure their angular distribution.
Fundamental parameters

Fit function:

$$M(\phi) = A + B \cos^2(\phi - \phi_0)$$

$$\frac{M_{\text{max}} - M_{\text{min}}}{M_{\text{max}} + M_{\text{min}}} = \frac{B}{B + 2A}$$

Polarization:

$$\frac{1}{\mu} \frac{B}{B + 2A} \quad \mu \text{ is the modulation factor, i.e. the modulation for 100\% polarized radiation}$$
The level at which it is possible to reject the hypothesis of a non-polarized source at the 99% confidence level is the Minimum Detectable Polarization (MDP) which measures the sensitivity to a given source in a given observing time \( T \):

\[
MDP = \frac{4.29 \sqrt{(S + B)}}{\mu S \sqrt{T}}
\]

- **99% confidence level.**
- **\([\mu]\) Modulation factor**
  - (max =1, Bragg, Thomson at 90°, Photoelectric effect)
- **\([S]\) Source Counting Rate**
  - (large area or large collector, strong sources)
- **\([B]\) Background counting rate**
  - (collimation, good background rejection or small polarimeters in focal plane, high collecting/active area)
- **\([T]\) Observing Time**
  - (typical unit is \(10^5\) s)
**X-ray polarimetry with a Gas Pixel Detector**

A photon crosses a Beryllium window and it is absorbed in the gas gap, the photoelectron produces a track. The track drifts toward the multiplication stage that is the GEM (Gas Electron Multiplier) which is a insulator foil metallized on both side and perforated by microscopic holes (30 um diameter, 50 um pitch) and it is then collected by the pixellated anode plane that is the upper layer of an ASIC chip.

**1-cm drift, 1-bar.**

**He-DME (20-80) 2-10 keV.**

Polarization information is derived from the angular distribution of the emission direction of the tracks produced by the photoelectrons that brings memory of the X-ray polarization. The detector has a very good imaging capability.
The chip is self-triggered and low noise. The top layer is the collection plane. The bottom 4 layers are a complete analogue chain for each pixel with preamplifier/shaper/sample and hold and serial readout.

It defines the sub-frame that surrounds the track. The dead time downloading an average of 1000 pixels is 100 time lower than for 1E5 pixels.
Tracks analysis

From the analysis of the track we reconstruct the original direction of the photoelectron (blue line) and the impact point (blue cross).

\[
\frac{\partial \sigma}{\partial \Omega} = r_0^2 \frac{Z^5}{137^4} \left( \frac{mc^2}{h \nu} \right)^2 \frac{4\sqrt{2} \sin^2(\theta) \cos^2(\varphi)}{(1 - \beta \cos(\theta))^4}
\]

1) The track is collected by the ASIC.

2) Baricenter evaluation (using all the triggered pixels).

3) Reconstruction of the principal axis of the track: minimization of the second moment of charge distribution.

4) Reconstruction of the conversion point: third moment along the principal axis (asymmetry of charge distribution to select the lower density end) + second moment (length) to select the region for conversion point determination.

5) Reconstruction of emission direction: (minimization of the second moment with respect to the conversion point) but with pixels weighted according to the distance from it.
IAPS-Rome facility for the production of polarized X-rays.

<table>
<thead>
<tr>
<th>keV</th>
<th>Crystal</th>
<th>Line</th>
<th>Bragg angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.65</td>
<td>ADP(101)</td>
<td>CONT</td>
<td>45.0</td>
</tr>
<tr>
<td>2.01</td>
<td>PET(002)</td>
<td>CONT</td>
<td>45.0</td>
</tr>
<tr>
<td>2.29</td>
<td>Rh(001)</td>
<td>Mo Lα</td>
<td>45.3</td>
</tr>
<tr>
<td>2.61</td>
<td>Graphite</td>
<td>CONT</td>
<td>45.0</td>
</tr>
<tr>
<td>3.7</td>
<td>Al(111)</td>
<td>Ca Kα</td>
<td>45.9</td>
</tr>
<tr>
<td>4.5</td>
<td>CaF₂(220)</td>
<td>Ti Kα</td>
<td>45.4</td>
</tr>
<tr>
<td>5.9</td>
<td>LiF(002)</td>
<td>⁵⁵Fe</td>
<td>47.6</td>
</tr>
<tr>
<td>8.05</td>
<td>Ge(333)</td>
<td>Cu Kα</td>
<td>45.0</td>
</tr>
<tr>
<td>9.7</td>
<td>FLi(420)</td>
<td>Au Lα</td>
<td>45.1</td>
</tr>
<tr>
<td>17.4</td>
<td>Fli(800)</td>
<td>Mo Kα</td>
<td>44.8</td>
</tr>
</tbody>
</table>

Facility at IASF-Rome/INAF

Close-up view of the polarizer and the Gas Pixel Detector

Capillary plate (3 cm diameter)

Aluminum and Graphite crystals.

Spectrum of the orders of diffraction from the Ti X-ray tube and a PET crystal acquired with a Si-PiN detector by Amptek

(Muleri et al., SPIE, 2008)
Modulation factor measurements and simulations

![Graph showing modulation factor vs energy]
Energy resolution stability of the Low Energy GPD
A Gas Pixel Detector for higher energies (6-35 keV)

Current prototype
Argon 70% DME 30% 2 cm, 2 bar

Goal
- Argon mixture @ 3 bar
- Gas cell thickness 3 cm
- new ASIC (already being manufactured)
  - Reduce the ROI
  - Increase the clock

Spectroscopy: <20% @ 6 keV
Timing: 8 μs
Dead-Time: 50 μs

Efficiency (dashed) and modulation Factor (solid) with Monte Carlo and measurement for the low energy (2-10 keV) polarimeter and medium energy (6-35 keV) polarimeter.
MEP

Real tracks @ 22 keV

$^{55}\text{Fe}$ Unpol.

Polarized 9.7 keV

9/23/2014 ESA-CAS 2nd workshop
Siming Liu (PMO) Paolo Soffitta (IAPS)
We propose to make a measurement in an energy range starting where the non-thermal emission starts to dominate the flare spectrum.

Medium Energy Polarimeter (MEP)
Ar-DME gas mixture
Pressure 3 bar (prototype 2 bar)
Absorption gap thickness 3 cm (prototype 2 cm).

<table>
<thead>
<tr>
<th>Flare Class</th>
<th>Maximum X-Ray Flux (W/m²)</th>
<th>Maximum X-Ray Flux (ergs/cm²-s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X10</td>
<td>$n \times 10^{-8}$</td>
<td>$n \times 10^{-5}$</td>
</tr>
<tr>
<td>X5</td>
<td>$n \times 10^{-7}$</td>
<td>$n \times 10^{-4}$</td>
</tr>
<tr>
<td>X1</td>
<td>$n \times 10^{-9}$</td>
<td>$n \times 10^{-3}$</td>
</tr>
<tr>
<td>M5.2</td>
<td>$n \times 10^{-3}$</td>
<td>$n \times 10^{-2}$</td>
</tr>
<tr>
<td>M1</td>
<td>$n \times 10^{-4}$</td>
<td>$n \times 10^{-1}$</td>
</tr>
</tbody>
</table>

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<th>MDP (%)</th>
<th>Integration time (s)</th>
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<td>489.1</td>
</tr>
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<td>46.4</td>
<td>128.0</td>
</tr>
</tbody>
</table>
Energy Dependent Sensitivity of the SEEPE X-ray polarimeter

Model from Zharkova et al., 2010

Hard spectrum
Soft spectrum

Solid: Collision; dotted collision and return current;
Dashed: Collision and converging magnetic beam
Dash-dotted: all
X5.1 Flare

**MDP (%) = 4.2 ; 2.4 ; 4.2; 4.6; 3.3; 7.1; 17.9; 25.4**

**15-35 keV**
Scientific Payload

Electron-Proton and High-Energy Telescopes (Transport) (EPT-HET)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>2.5 kg</td>
</tr>
<tr>
<td>Power</td>
<td>5 W</td>
</tr>
<tr>
<td>Energy Range</td>
<td>Electrons: 20 keV – 30 MeV</td>
</tr>
<tr>
<td></td>
<td>Protons: 20 keV – 100 MeV</td>
</tr>
<tr>
<td></td>
<td>Heavy ions: ~10 MeV/nuc – ~200 MeV/nuc (species dependent)</td>
</tr>
<tr>
<td>Time Resolution</td>
<td>10s (species dependent)</td>
</tr>
</tbody>
</table>
Supra-Thermal Electrons & Protons (STEP)  
(Transport, Local Acceleration)

- **Mass**: 2.5 kg
- **Power**: 5 W
- **Energy Range**:
  - Electrons: 2 keV – 100 keV
  - Protons: 3 keV – 100 keV
- **Time Resolution**: 10s (species dependent)
Magnetometer

**Linearity Test**

<table>
<thead>
<tr>
<th>Magnetic Field Range</th>
<th>Better than ±65000nT</th>
</tr>
</thead>
<tbody>
<tr>
<td>noise</td>
<td>&lt;30pT/√Hz @1Hz</td>
</tr>
<tr>
<td>mass</td>
<td>1kg</td>
</tr>
<tr>
<td>power</td>
<td>&lt;1.5W/detector</td>
</tr>
</tbody>
</table>

**Power Spectrum of Noise**
### SEEPE

#### High Energy Band Spectrometer (HEBS)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>$362 \times 349 \times 172.5\text{mm}$</td>
</tr>
<tr>
<td>Weight</td>
<td>20.5 kg</td>
</tr>
<tr>
<td>Power</td>
<td>20 W</td>
</tr>
<tr>
<td>Telemetry</td>
<td>2 GB/day</td>
</tr>
<tr>
<td>Energy Range</td>
<td>10keV - 600MeV</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>3%@662keV</td>
</tr>
<tr>
<td>Temporal Resolution</td>
<td>1s (quiescent), 32ms (flare-mode)</td>
</tr>
<tr>
<td>Effective Area</td>
<td>&gt;60cm$^2$@1MeV</td>
</tr>
<tr>
<td>Sensitivity (300keV-10MeV)</td>
<td>Better than $3 \times 10^{-3}$ photos/cm$^2$/s</td>
</tr>
</tbody>
</table>

#### X-ray Polarimeter (Gas Pixel Detectors)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>16 kg</td>
</tr>
<tr>
<td>Power</td>
<td>25 W</td>
</tr>
<tr>
<td>Energy Range</td>
<td>10-35keV (for non-thermal bremsstrahlung)</td>
</tr>
<tr>
<td>Mass Memory</td>
<td>2.5 GB to be downloaded sporadically (1-2/month)</td>
</tr>
</tbody>
</table>

#### Electron and Ion Detectors

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPT-HET</td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>2.5 kg</td>
</tr>
<tr>
<td>Power</td>
<td>5 W</td>
</tr>
<tr>
<td>Telemetry</td>
<td>1.5 kbps</td>
</tr>
<tr>
<td>Time Resolution</td>
<td>10s (species dependent)</td>
</tr>
<tr>
<td>Geometry Factor [cm$^2$ sr]</td>
<td>EPT: 2 x 0.01, HET: 3 x 0.21 (protons), HET: 2 x 0.26 (heavy ions)</td>
</tr>
<tr>
<td>Magnetoimeter</td>
<td>1kg 1.5W/detector ± 65000nT</td>
</tr>
</tbody>
</table>

#### Total

- **Total Weight**: 43.5 kg
- **Total Power**: 56.5 W
## Launcher and Orbit

<table>
<thead>
<tr>
<th>Plan</th>
<th>One</th>
<th>Two</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit</td>
<td>~700km</td>
<td>Lunar Resonance</td>
</tr>
<tr>
<td>Launcher</td>
<td>Long March 2</td>
<td>Vega or equivalent with propulsion module.</td>
</tr>
<tr>
<td>Cost</td>
<td>~10M Euro (1st institute)</td>
<td>Under study</td>
</tr>
<tr>
<td>Bus</td>
<td>~10M Euro (DongFangHong or Shanghai Mini-satellite institute)</td>
<td>CGS/OHB/under study.</td>
</tr>
<tr>
<td>Issues</td>
<td>Without Particle Detectors and Magnetometer</td>
<td>more complicated mission profile, more resources needed for the spacecraft, included satellite transmission.</td>
</tr>
</tbody>
</table>
An example of platform that among others is compliant with the mission requirements.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit</td>
<td>from 600 to 1050 km for SSO</td>
</tr>
<tr>
<td>Max payload mass</td>
<td>up to 70 kg</td>
</tr>
<tr>
<td>Payload envelope (h; w;l)</td>
<td>Cylindrical shape with an envelope of Ø 0.64 m x L 1.3 m</td>
</tr>
<tr>
<td>Average payload power</td>
<td>60 W</td>
</tr>
<tr>
<td>Max Bus dry mass (Hydrazine)</td>
<td>159 kg; (13 kg)</td>
</tr>
<tr>
<td>Pointing accuracy (control)</td>
<td>2.2 arcmin</td>
</tr>
<tr>
<td>Attitude determination (knowledge)</td>
<td>50 arcsec</td>
</tr>
<tr>
<td>Pointing stability (drift)</td>
<td>1 arcsec/s</td>
</tr>
<tr>
<td>Maximum Radiation total dose</td>
<td>10 krad</td>
</tr>
<tr>
<td>TC&amp;R description, frequency band and rates</td>
<td>S band DWLK: 2,29 GHz for 570 Kbps; Sband UPL: 2,1 4 kbps X band transmission could be implemented</td>
</tr>
</tbody>
</table>
SEEPE
Schedule

• Study phase: 2016-2017
• Implementation phase: 2018-2021
• Launch: 2021

The next solar cycle starts near 2021!
Complementary Missions

- SDO (2010- )
- IRIS (2013- )
  Magnetic Fields.
  Thermal Emission.
- Solar Orbiter
- Solar Probe + ( ~2018- )
  <0.3 AU.
  STIX: X-ray Images; EPD: electrons, protons, ions.
  Solar Wind Electrons Alphas and Protons Investigation.
- Advanced Solar Obs. (2020-) 1.0AU, X-ray Imager.
Complementary Observations

• Radio
  Gyro-synchrotron and Bremsstrahlung
  Magnetic Fields, Energetic Electron Beams

• Hα
  Irradiation by X-ray and Heating by energetic particles

• Optical (ATST)
  Energetics of thermal and non-thermal particles
Team

Science and Data Analysis:
Siming Liu, Youping Li, Weiqun Gan (PMO, CAS), Linghua Wang (PKU), Gang Qin (NSSC), Chuan Li (NJU), China, Valentina Zharkova Northumbria University, Newcastle, UK, Giovanni Peres, Fabio Reale (Universita’ di Palermo), IT

High Energy Band Spectrometer:
Jian Wu, Jin Chang Purple Mountain Observatory, China

X-ray Polarimeter:
Paolo Soffitta, Enrico Costa, Sergio Fabiani, Fabio Muleri Istituto Di Astrofisica e Planetologia Spaziali (IAPS)
Ronaldo Bellazzini, Alessandro Brez, Massimo Minuti, Michele Pinchera, Gloria Spandre (INFN–Pisa)

Electron-Proton and High Energy Telescopes and STEP:
Robert F. Wimmer-Schweingruber Institut fuer Experimentelle und Angewandte Physik, University of Kiel, Germany

Magnetometer:
Yong Liu National Space Science Center, CAS, China
Summary

Solar Energetic Emission and Particles Explorer (SEEPE) is a timely mission suitable for the ESA and CAS joint scientific space mission:
1) The proposed mission meets the boundary conditions and draws on expertise in both China and Europe;
2) The scheduled launch time matches the onset of the next (25th) solar cycle;
3) It is highly complementary to the ESA’s Solar Orbiter, NASA’s Solar Probe Plus, CAS’s ASO missions for the 25th solar cycle;
4) The timing, spectral, polarization, and energetic particles observations of the solar activity, in coordination with other ground and space based observations, will help to reveal how the space weather is driven by the Sun.
Solar flare mechanisms
only reconnection can account for directivity of accelerated particles

The presence of **hard X-ray emission** and **gamma emission** at the bottom of coronal loops indicates the presence of highly directed electrons and protons in solar flares.
Evolution of photon spectrum and polarization degree spectrum for photons at $\vartheta = 90^\circ$ with respect to B for **soft** and **hard** electron beam.

- **Time**
  - Dotted => down-ward e$^-$
  - Dashed => up-ward e$^-$
  - Solid => total photon emission
Particle in cell simulation (PIC, Siverski and Zharkova 2009)

Simulations reveal that, during acceleration appears a polarisation electric field which is responsible for separating electron from proton with narrow pitch angle (p.a, angle between the B and v of particles, positive cosine downward) distribution.
Photoelectric effect

Polarimetry based on photoelectric effect was tempted very long ago but it is now a mature technology.

An X-ray photon directed along the Z axis with the electric vector along the Y axis, is absorbed by an atom.

The photoelectron is ejected at an angle $\theta$ (the polar angle) with respect the incident photon direction and at an azimuthal angle $\phi$ with respect to the electric vector.

If the ejected electron is in ‘s’ state (as for the K–shell) the differential cross section depends on $\cos^2(\phi)$, therefore it is preferentially emitted in the direction of the electric field.

Being the cross section always null for $\phi = 90^\circ$ the modulation factor $\mu$ equals 1 for any polar angle.

By measuring the angular distribution of the ejected photoelectrons (the modulation curve) it is possible to derive the X-ray polarization.
Hard X-ray polarimetry as a diagnostic of electron beams precipitating from the corona down to the solar chromosphere

Slides extracted from and with the help of Valentina Zharkova.

Material from:
Siversky, T.V. & Zharkova V.V., JPP, 2009