AdEPT
Advanced Energetic Pair Telescope

A Discovery Mission for Medium-Energy Gamma-Ray Polarimetry

Andrey Timokhin
on behalf of AdEPT team

Future Space-based Gamma-ray Observatories
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AdEPT Science: Why MeV?

- The MeV sky is largely unexplored:
  - new class of sources?
  - different emission regions

- Many Fermi sources indicate peaks in MeV range

- Optimal energy band for γ-ray polarimetry

- $\pi^0 \rightarrow \gamma\gamma @ E \sim 67.5$ MeV
AdEPT Science: Survey with Polarimetry

Energy Range: 2-500 MeV
- Poorly explored domain
  - Detailed look at known accelerators: PSRs, PWNs, SNR, AGN, GRBs
  - Yet unseen accelerators
    - Polar cap emission in PSRs
    - Magnetars
    - New classes of sources
- $\pi^0 \rightarrow \gamma \gamma \at \ E \sim 67.5 \ MeV$
  $\pi^0$ - telltale signature of hadrons
  - Leptonic vs. Hadronic acceleration scenarios
  - Dark Matter photon mediators

Polarization: 0.1% MDP
- Polarization measurements:
  Geometry of accelerators
  no foreground propagation effects
- Strict limits on polarization:
  Distinguishes $\pi^0$ emission
  $\pi^0 \rightarrow \gamma \gamma$ is unpolarized
- Unique test of relativity
  vacuum birefringence effect

Angular Resolution: $\sim 0.2^\circ$
- Excellent source localization down to $\sim 1'$ ($0.2^\circ/\sqrt{N_{ph}}$)
- Resolving MeV background
- Dark Matter profiles

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Polarization helps to discriminate between Emission Mechanisms

<table>
<thead>
<tr>
<th>Synchrotron Radiation:</th>
<th>Curvature Radiation:</th>
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<tbody>
<tr>
<td>polarization up to 75%</td>
<td>polarization up to 100%</td>
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<tr>
<td>$E \perp B$</td>
<td>$E \parallel B$</td>
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<tr>
<th>Inverse Compton Scattering:</th>
<th>$\pi^0 \rightarrow \gamma + \gamma$ complete polarization</th>
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<tbody>
<tr>
<td>Scattering Polarized radiation (SSC)</td>
<td>completely unpolarized</td>
</tr>
<tr>
<td>polarization up to 50%</td>
<td></td>
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<tr>
<td>Scattering Unpolarized radiation – low polarization &lt; 1%</td>
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Pulsar Physics

AdEPT will determine the structure of pulsar acceleration zones in the inner and outer magnetosphere by measuring the gamma-ray polarization.

GeV gamma-rays come from the outer magnetosphere. *Fermi* results suggest strong emission at MeV energies.

10 - 100 MeV gamma-rays from the inner magnetosphere (Polar Caps) are predicted in all pulsar theories.

Instrument Requirements:
- MDP Polarization sensitivity ~1%
- Polarization angle accuracy ~10°
- Timing resolution ~1-10 msec
- Energy range 10-100 MeV
- Energy Resolution ~20%
- Angular resolution < 1 deg
- FOV ~$2\pi$ sr
Pulsar Physics

Polar Cap emission

Phase-resolved polarization
Pulsar Physics

transition between emission mechanisms

Polar Cap emission

Outer magnetosphere emission

curvature radiation

the rest -synchrotron radiation

(Timokhin & Harding ‘15)

(Harding & Kalapotharakos ‘15)
AdEPT will determine the cosmological evolution of AGNs and GRBs by mapping the magnetic fields and distinguishing between leptonic and hadronic processes.

(Zhang & Boettcher ‘13)
AdEPT will search for Galactic dark matter in the Milky Way center and halo by looking for a MeV gamma-ray annihilation signature of dark photon mediators.
Other Science Goals

• **Galactic Diffuse Emission**
  – Study star formation and cycle of matter
  – Resolve source contribution to Galactic diffuse emission
  – Distinguish Galactic regions where leptonic vs. hadronic processes are dominant

• **Time Domain Astronomy**
  – Observe entire sky every orbit
  – Gamma Ray Bursts

• **Exotic Physics**
  – Test physics around neutron stars, magnetars, and black holes
  – Test limits of Relativity (Lorentz invariance)
AdEPT MIDEX and Prototype

Prototype, 1/16 of MIDEX instrument Engineering unit
AdEPT Instrument

- AdEPT is a simple instrument, only 4 mechanical structures
  - Gas pressure vessel
    - Cylinder, Field shaping grid on internal surface
    - Upper and lower domes
  - Upper readout plane
  - Common high voltage plane
  - Lower readout plane
  - Electronics
  - On-board computer processing

Instrument Detector Physics

- **Enabling technology** is 3-DTI, Three-Dimensional Track Imager
  - Large volume gaseous TPC
    - Ionization chamber
  - Micro-Well Detector (MWD) readout
    - 2-D Proportional counter (PC)
    - Z-coordinate from drift time
  - \( \text{Ar} + \text{CS}_2 \) at 1.5 atm
    - Ar – active detection medium
    - Chemically inert, no gas deterioration
    - CS\(_2\) negative ion molecule
    - Dramatically reduces diffusion → increased detector volume
AdEPT Heritage

Demonstration of 3-DTI for neutron imaging - 2011

Electron Tracking in 3-DTI

X-Z, & Y-Z projections of single electrons from $^{90}\text{Sr}$ in Ar + CS$_2$ with 0.4 mm resolution

X-Z projection of 6.129 MeV gamma interaction in 80% P-10 + 20% CS$_2$
Principle of Polarization Measurement

- Polarization is encoded in the azimuthal angle of the pair.

- Direction of the pair must be measured before being confused by Coulomb scattering, in < 1 mRL.

1 mRL:
- ~100 μm of Si (< 1 track coordinate)
- ~80 mm of Ar at 1.5 atm (200 track coordinates)
Enabling Long Drift Distance
by adding an electronegative component to the gas

- $\text{CS}_2$ captures ionization electrons, forming negative ions, which drift in thermal equilibrium with the gas.
- Diffusion decreases with increasing drift field and is independent of gas mixture
Baseline Gas Options

• Gas, Noble gas preferable
  – Chemically inert
    • He, Z=2, difficult to seal PV
    • Ne, Z=10, costly
    • Ar, Z=18, cheap
      • Kr, Z=36, radioactive, costly
      • Xe, Z=54, negative ion drift velocity too low (~2 m/s)
      • Rn, Z=86, radioactive, negative ion drift velocity way too low

• Negative ion additive
  – Gas or low vapor pressure
  – Low-ish electronegativity
    • CH$_2$NO$_2$
    • CS$_2$, Z=40
    • O$_2$, Z=8, appealing, untested
AdEPT Baseline Performance

Effective Area (cm$^2$)

Fermi-LAT front, P7SOURCE_V6 (FSSC)

EGRET, Thompson, et al. (1993)

AdEPT, 8 m$^3$ vol Ar+CS$_2$ at 1.5 atm

Point Source Sensitivity (MeV cm$^{-2}$ s$^{-1}$)

3σ significance,
$T_{\text{obs}}=10^6$ s, and $\Delta E = E$,
$\Phi_{\text{egb}}=2.7 \times 10^{-3} (E/1 \text{ MeV})^{-2.1}$

No correction for inefficiencies in track recognition

Minimum Detectable Polarization (%)

$\lambda = 0.15$

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AdEPT Angular Resolution

- AdEPT will achieve angular resolution approaching the kinematic limit, the best allowed by the physics

- Equivalent of “diffraction limited” optics!

AdEPT will achieve ~0.7° at ~70 MeV in Ar at 1.5 atm
AdEPT Mission Realization

- Gas volume: 8 m³
- Instrument: 995 kg
  Spacecraft: 445 kg
- 600 km circular LEO, 28° inclination
  zenith pointed, scanning mode operation
- Falcon-9 rocket
- Fits within MIDEX constraints
AdEPT Technologies
new science - new technology

1. Composite Pressure Vessel
2. Field Shaping Grid
3. Micro-Well Detector
4. ASIC and FPGA
5. On-Board Processing
Micro Well Detector Approach

• Ionization from charged particles drifts to detectors and must be “read out”

• Micro Well Detectors (MWD)
  – 2-D readout from single detector
  – Active detector, gain up to $10^6$
Silicon Micro Well Detectors

- Pixel size related to diffusion
  - Pitch: 400 µm ≈ 1/2 electron cloud diffusion over 100 cm drift
  - Well diameter: 1/4-1/8 of pitch,
  - Well depth (aspect ratio), ~1:1 empirically determined

- Inorganic SiMWD
  - Inorganic materials
  - Take advantage of commercial silicon wafer technology
SiMWD Fabrication

• Use inorganic materials
  • SiO$_2$ insulator, surrounding Si posts
  • Au electrodes
  • Etch away Si posts to form wells
  • All electrodes accessible from top surface

• Packaging
  • Bonding SiMWDs to substrate
  • Wire bonds for electrode-electrode interconnect electrodes and electrode-PCB

First DDL engineering unit, Dec. 2014
On-Board Processing (OBP) must discriminate $\gamma$-rays from cosmic rays to generate science data

- Tracks drift to MWD and must be “read out”
  
  **No trigger possible**

- Negative ion technique
  - Enables long drift distance $\sim 1\text{m}$
  - Reduces drift velocity $\times 10^3$, $\sim 16 \text{ m/s}$
  - Total drift time is $\sim 50 \text{ ms}$
  - Increases occupancy of CR tracks

  **Anti-coincidence not viable**

- Streaming Mode Operation
  - Gb/s raw data rate
  - No readout dead-time
OBP, Approach

Raw X-Z or Y-Z Data, Digitized ASIC Signals

- Noise Suppression
- Detector Hits
  - 2-D Track Finding “Cellular Automaton”
    - “Level-1” FPGA, FEE Card

Track Data

- Co-Registration
  - 3-D Track Finding “Cellular Automaton”
    - 3-D Track Fitting “Kalman Filter”
      - 3-D Track Subtraction “Remove Cosmic Rays”
        - Residual Data, Includes Gamma-Ray Events
          - Telemeter to ground

Ground Processing

- Science Data D, E, P, T
  - “Level-3” Science Processing

Reconstruction Pipeline

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Cellular Automaton Advantages

- Simple, Vector based (fast)
- Intrinsically parallel
- Performed locally on the FPGA of the FEE
- Useful for complicated event topologies
<table>
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<tr>
<th>Science Requirement</th>
<th>Physical parameter</th>
<th>Detector requirement</th>
<th>Instrument requirement</th>
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<tbody>
<tr>
<td>Energy range 2-500 MeV</td>
<td>Pair production</td>
<td>3-D tracking of e-/e+ pair</td>
<td>3-D position of ionization electrons</td>
</tr>
<tr>
<td>Highest achievable polarization sensitivity</td>
<td>Measure pair azimuthal angle in &lt; 1 mRL</td>
<td>Accurate tracking, high granularity</td>
<td>Minimize electron diffusion, low density medium</td>
</tr>
<tr>
<td>Best angular resolution</td>
<td>Limited by recoil momentum</td>
<td>Minimize Coulomb scattering</td>
<td>Low density interaction medium</td>
</tr>
<tr>
<td>Isotropic performance</td>
<td>No preferred tracking direction, $2\pi$ sr FOV</td>
<td>Isotropic interaction medium, omni-directional tracking</td>
<td>100 % active conversion medium, no passive material</td>
</tr>
<tr>
<td>Substantial improvement in continuum sensitivity</td>
<td>Large geometric area, large interaction volume, best angular resolution</td>
<td>Minimize distortion due to electron diffusion</td>
<td>Negative ion drift, large active volume</td>
</tr>
<tr>
<td>Energy resolution to resolve pi-zero feature</td>
<td>$\Delta E/E$ better than 30%</td>
<td>Measure Coulomb scattering of tracks over large distances</td>
<td>Energy $\propto$ Coulomb scattering, large active volume</td>
</tr>
</tbody>
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The AdEPT is a mission aimed at studying the complete photon signature.