ASTENA, a new mission concept for an Advanced Surveyor of Transient Events and Nuclear Astrophysics

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on behalf of
an International Collaboration

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ASTENA Collaboration

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In the framework of AHEAD WP9 devoted to Gamma-ray Astronomy, a Scientific Advisory Group was established to suggest top-priority themes. They resulted to be:

- Gamma-Ray Bursts and
- Nuclear Astrophysics.

An AHEAD call for instrument/mission concepts was issued.

ASTENA is one of the three accepted mission concepts for which a feasibility study has been supported.

The others two are ASCI (All-Sky Compton Imager), and PACT (Pair and Compton Telescope).
ASTENA in flight configuration

- Wide Field Monitor-Imaging Spectrometer (WFM-IS) (18 units).
- Narrow Field Telescope (NFT)
- Focal plane PSD on a deployable boom
ASTENA folded configuration (before the launch)

Exploded view

ASTENA accommodation within the Soyuz fairing
WFM-IS general features

• **Energy band**: 2 keV-20 MeV

• **Total effective area**: ~ 2 m²

• **Three-dimensional PSD** (~1 mm resolution)

• **At low energies** (<100 keV), imaging capabilities by means of a dual scale coded mask (FOV > 1 sr):
  - 1 arcmin PSLA up to 30 keV (crucial for NFT follow-up);
  - 5 arcmin PSLA 30-100 keV.

• **At high energies** (>200 keV):
  - Compton kinematics for crude direction determination

• **Polarimetric capabilities**
WFM-IS concept (similar to THESEUS XGIS)

SDD Pulse height spectrum

PET diffracted spectrum

CsI Pulse height spectrum

Pulse shape spectrum
Angular response of a single WFM-IS unit and of a group of 3 units

Orientation of the block units

Angular response up to 100 keV

± 20° offset wrt the optical axis
WFM-IS expected continuum sensitivity
Narrow Field Telescope (NFT)

- Based on **Laue lens with bent crystals of Ge(111) and Si(111)**
  - Crystal tiles: 2 mm thick, 10x30 mm² cross section
  - 3 m Diameter
  - Focal length: 20 m (extendable boom)
  - Energy band: 50-600/700 keV
  - Projected geometric area: ≈7 m²

- **Focal plane detector** with:
  - High detection efficiency (>80%)
  - 3D PSD (spatial resolution of 300 µm in (x,y,z).
  - Energy resolution: 1% @511 keV

Virgilli+2017, JATIS 3(4), 044001
Khalil+2015, NIM A 786, 59
Lens development status

See Talk by Virgilli
On axis PSF

Flat crystals

Bent crystals with curvature radius equal to lens radius
Angular resolution = 30”
NFT field of view

FOV = 3.6 arcmin
Focal plane PSD

- Proposed solution:
- 4 layers of an array of 4x16 CZT elements:
  - 0.5x2 cm² cross section
  - 2 cm thick
- Drift strip configuration for the anodes and orthogonally segmented cathodes in Parallel Transverse Field (PTF) (Kuvvetli+2014)
CZT focal plane detector

- **PSD size:**
  - Cross section: 8x8 cm²
  - Sensitive thickness: 8 cm

- **Status:** prototype under development and testing
ASTENA/NFT expected sensitivity

\[ T = 10^5 \text{ s}, \quad \Delta E = E/2 \]
### Sensitivity to lines ($3\sigma$, $10^5$ s) (ph/cm$^2$ s)

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Conf (a)</th>
<th>Conf(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>3.7 x 10^{-7}</td>
<td>7.4 10^{-7}</td>
</tr>
<tr>
<td>200</td>
<td>2.3 x 10^{-6}</td>
<td>4.6 x 10^{-6}</td>
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<tr>
<td>300</td>
<td>4.6 x 10^{-6}</td>
<td>9.3 x 10^{-6}</td>
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<tr>
<td>400</td>
<td>1.2 x 10^{-5}</td>
<td>2.3 x 10^{-5}</td>
</tr>
<tr>
<td>500</td>
<td>2.3 x 10^{-5}</td>
<td>4.9 x 10^{-5}</td>
</tr>
</tbody>
</table>

Virgilli+2017, JATIS
ASTENA/NFT polarization sensitivity

(90-600 keV, 3D PSD 10x10 cm² cross section, 10 cm thickness)

Polarization modulation factor $Q$:

$$Q = \frac{C_{\text{max}}^{100} - C_{\text{min}}^{100}}{C_{\text{max}}^{100} + C_{\text{min}}^{100}}$$

Polarization level:

$$P = \frac{Q_p}{Q_{100}}$$
Key science cases
(paper in preparation)

- **Transient events:**
  - High energy spectrum and polarization of the GRB afterglow emission;
  - Hard X-ray polarization of the GRB prompt emission
  - Deep search of very Low Luminosity GRBs (llGRBs)
  - Search of prompt emission, if any, from Fast Blue Optical Transients (FBOTs)
  - Deep search of Electromagnetic Counterparts of Gravitational Wave Events
  - Deep search of gamma-ray counterparts of Fast Radio Bursts (FRBs)
In the case of **990123**, only synchrotron was insufficient (Corsi+2005).
In the case of **130427A**, synchrotron is sufficient at NuSTAR energies but NuSTAR is crucial to constrain the SED spectral shape (Kouveliotou+2013).
Fast Blue Optical Transients (FBOT)

- FBOTs: likely a new class of transient sources due to the recent discovery of AT2018cow (ATel 11727, Margutti+2018)
- AT2018cow is rapidly evolving, with luminosity rivalling Ibc-Sne.
  - Hard X-ray counterpart consistent with an X-ray afterglow (power-law spectrum).
  - No evidence of a prompt gamma-ray emission
  - New class of low luminosity GRBs?

\[
L \sim 4 \times 10^{44} \text{ erg/s}
\]
Nuclear Astrophysics

- Determination of the origin of the 511 keV positron annihilation diffuse line from Galactic Center region. Thanks to the NFT sensitivity and angular resolution (30") test of:
  - Emission from point-like sources, eg, microquasars?
  - Truly diffuse emission? DM annihilation?

- Study of intensity and time behavior of the 158 keV line ($^{56}\text{Ni}\rightarrow^{56}\text{Co}$) emitted at early times ($T_{1/2}=6.1$ d) in Type 1a supernova explosions.

Indirect detection of DM

Understanding the nature of Dark Matter with ASTENA

X

anti-X

\[ \gamma, \nu_e, \nu_\mu, \nu_\tau, e^+, e^-, \text{X-ray} \]

Excess of \( \gamma \)-rays

Fermi two-year all-sky map

\( \text{GeV} \)

\( \text{KeV} \)

Sensitivity

Angular resolution

Broad band

ASTENA
Some other science cases (Legacy science)

- **Origin of the high energy component of magnetars**
- **Hard X-/soft gamma-ray spectral properties of AGN**
  - High energy cutoff of radio quiet AGN (Seyfert and QSO)
  - Blazar hard X-/soft gamma-ray spectrum (still unknown)
  - CXB at high energies (above the 30 keV CXB peak)
- **Ample space for the discovery of new classes of source and new phenomena**
Emission physics and nature of Blazars

- Two humps in the SED:
  - mm-soft X-ray: synchrotron emission
  - 100 keV-TeV: IC (seed photons: disk, jet, BLRs)
- The variation of the overall SED at increasing $L_{\text{bol}}$ is linked to $M$, $\dot{M}$, with $L_{\text{jet}} \sim \dot{M} c^2$
- Observations at 100-600 keV critical for:
  - physics of FSRQs vs BL Lacs
  - contribution of Blazars to XRB at $\sim 100$ keV

Low power BL Lacs have S peak at keV or higher, thus are best TeV candidates
CXB ( E>50 keV)

- Spectral synthesis models are increasingly degenerate above the CXB peak: A single energy cutoff is assumed.
- Attempts to explain the CXB at E>30 keV with Blazars unsatisfactory: spectrum at hard X-rays still unknown
- Direct determinations of spectral shapes at 50-600 keV at different $L_X$ (and $z$), essential to complete the cosmic history of accretion power
  → feasible with ASTENA
Conclusions

• **ASTENA** is the first mission concept based on a broad band hard X-/soft gamma-ray optics (50 keV-600/700 keV)

• It opens a new window in the high energy astrophysical research.

• **It explores the high energy transient sky** (prompt and afterglow emission of classical short and long GRBs, llGRBs, FBOTs, TDEs ...) and its properties (spectrum, light curve, polarization, etc) with unprecedented sensitivity.

• For the first time in the soft gamma-ray band it improves
  – the point source localization accuracy below 1 arcmin.
  – The continuum spectrum sensitivity orders of magnitudes better than the current instrumentation.

• Thanks to its angular resolution in gamma-rays, the origin of the positron annihilation line from the GC region (a mystery 50 yrs old) can be established