MeV Astronomy
The INTEGRAL Perspective

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INTEGRAL
INTErnational Gamma Ray Astrophysics Laboratory

- Launched in October 2002
- ESA Mission with U.S. participation 1995 - 2010
- Four scientific instruments with wide X-ray through soft $\gamma$-ray (3 keV – 10 MeV) + optical coverage
- Unprecedented combination of spectral and spatial resolution
- All instruments fully operational 12 years after launch.
Scientific Instruments

Primary Instruments:

1. **SPI**: Spectrometer on INTEGRAL - High-Resolution Spectrometer (18 keV – 8 MeV)
2. **IBIS**: Imager on Board the INTEGRAL Satellite (15 keV – 10 MeV)

High Angular Resolution through Coded-Aperture Mask Technique

Secondary Instruments:

1. **JEM-X**: Joint European Monitor for X-rays (3 – 35 keV)
2. **OMC**: Optical Monitoring Camera
## Scientific Instruments

### Table 1: Summary of INTEGRAL Instrument Characteristics

<table>
<thead>
<tr>
<th></th>
<th>SPI</th>
<th>IBIS</th>
<th>JEM-X</th>
<th>OMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field of View (fully coded)</td>
<td>16°</td>
<td>8.3° × 8°</td>
<td>4.8°</td>
<td>5° × 5°</td>
</tr>
<tr>
<td>Angular Resolution (FWHM)</td>
<td>2.5°</td>
<td>12′</td>
<td>3′</td>
<td>23″</td>
</tr>
<tr>
<td>Energy Range</td>
<td>18 keV - 8 MeV</td>
<td>15 keV - 10 MeV</td>
<td>3 - 35 keV</td>
<td>500 - 600 nm (V filter)</td>
</tr>
<tr>
<td>Energy Resolution (FWHM)</td>
<td>1.93 keV @500 keV</td>
<td>8.0 keV @100keV</td>
<td>2.0 keV @22 keV</td>
<td>—</td>
</tr>
</tbody>
</table>


### Continuum sensitivities

![Graph showing continuum sensitivities for different instruments](image)

- **SIGMA**
- **ISGRI**
- **PICSIT**
- **OSSE**

**Dashed lines: prelaunch**

**3σ, 10^6 seconds**

**Sensitivity (photons cm⁻² s⁻¹ keV⁻¹)**

**Energy (keV)**

[Graph showing energy range and sensitivity](image)
Primary Scientific Goals

- High spatial and spectral resolution observations of Galactic $\gamma$-ray lines
- Hard X-ray observations of obscured (Galactic and extragalactic) X-ray sources
- Potential for X-ray polarimetry

Sources in the 1., 2., 3., 4. INTEGRAL IBIS/ISGRI Source Catalogues

<table>
<thead>
<tr>
<th>Source Type</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGN</td>
<td>250</td>
</tr>
<tr>
<td>CV</td>
<td>10</td>
</tr>
<tr>
<td>HMXB</td>
<td>80</td>
</tr>
<tr>
<td>LMXB</td>
<td>60</td>
</tr>
<tr>
<td>Other</td>
<td>20</td>
</tr>
<tr>
<td>Unknown</td>
<td>150</td>
</tr>
</tbody>
</table>
The INTEGRAL Sky

INTEGRAL Picture of the Month
March 2008
Gamma-Ray Lines – 511 keV

e^+e^- annihilation →
Sources of e^+ + annihilation (target) sites

Sources of e^+ generally thought to be SNRs – but different distribution than $^{26}$Al line...

Annihilation in a combination of different ISM phases

Jean et al. (2007)
Gamma-Ray Lines – 511 keV

INTEGRAL Picture of the Month May 2011
Gamma-Ray Lines – $^{26}$Al

Unveiling massive star nucleosynthesis in Cygnus X
1809 keV gamma-ray line emission from radioactive $^{26}$Al decay

**SPI/INTEGRAL 1809 keV line spectrum of Cygnus X**

Flux : $(7.2 \pm 1.8) \times 10^{-5}$ ph cm$^{-2}$ s$^{-1}$
Position : $1808.4 \pm 0.3$ keV $\Rightarrow v_{\text{rad}} = -41 \pm 50$ km s$^{-1}$
Width : $3.3 \pm 1.3$ keV $\Rightarrow \Delta v = 550 \pm 210$ km s$^{-1}$

DRAO radio image of ionising massive star clusters in Cygnus X that are at the origin of the $^{26}$Al production detected by SPI

Jürgen Knödlseder (on behalf of the INTEGRAL team), Centre d'Etude Spatiale des Rayonnements, Toulouse, France
Gamma-Ray Lines – $^{26}\text{Al}$

**SPI**

- First detailed spectroscopy of the $^{26}\text{Al}$ line
- Resolving Galactic rotation
- Identified core-collapse supernovae and their pre-explosion states as primary sources of $^{26}\text{Al}$.

INTEGRAL Picture of the Month January 2006
26Al Spectra along the Plane of the Galaxy

©SPI Team 2009

Cyclotron Lines

- At \( \sim 10 - 100 \text{ keV} \) for \( B \sim 10^{12} \text{ G} \)
- Direct diagnostic of \( B \) and physics of accretion column
- Variability constrains the location of line production region

Mowlavi et al. (2006)
Heavily Obscured Galactic Sources

Hard X-ray coverage allows for observations of near-GC sources and other XRBs up to > 100 keV.

Bouchet et al. (2009)

\[ 1E \ 1740.7-2942 \]

Bodaghee et al. (2010)

X-ray \( N_H \) often larger than inferred from optical extinction
→ Local absorption from companion wind
Supergiant Fast X-Ray Transients

Discovered by INTEGRAL: Highly variable HMXBs; possibly triggered by clumpy winds.

Blay et al. (2008)

IGR J18450-0435

INTEGRAL Picture of the Month August 2013
Magnetars
SGRs, AXPs

- $B > 10^{14}$ G
- Persistent emission + rapid outbursts
- INTEGRAL detects the faintest SGR bursts (about 1000 detected so far)
- First alert on the giant flare of SGR 1806-20 came from INTEGRAL
- Quiescent emission up to 200 keV

Götz et al. (2006)
Cataclysmic Variables (CVs)

- Roche-lobe filling star transferring matter to a White Dwarf (WD)
- Over 20 detected by INTEGRAL
- Most are Intermediate Polars (IPs), i.e., intermediate-B (~ $10^6$ G) WDs.
- Thermal bremsstrahlung from WD surface + emission from shock-heated material in the accretion column
- CVs might make significant contribution to Galactic Ridge X-ray Emission (GRXE)
- Symbiotic Binaries identified with accretion onto high-mass (~ 1.35 $M_\odot$) non-magnetic WDs - Candidate recurrent novae – Type Ia progenitors?
Heavily Obscured AGNs

IGR J19473-4452 / 2MASS Galaxy / z=0.05

Log NH \sim 23

IGR J13091+1137 / NGC 4992 / z=0.0225

Log NH \sim 24

INTEGRAL Picture of the Month
November 2005
Heavily Obscured AGN

- High-quality hard X-ray spectra from over 100 AGN, especially heavily absorbed (type-2) AGN

- Results consistent with thermal Comptonization in moderate Compton depth ($\tau \sim 0.5$), mildly relativistic corona

- Fraction of Compton thick sources smaller than expected from population synthesis models → hard Cosmic X-Ray background can not be entirely due to unresolved obscured AGN
AGN Studies
The optical – X-ray – $M_{\text{BH}}$ Fundamental Plane

Beckmann et al. (2009)
Blazars

- Large Energy range and MeV coverage important to resolve synchrotron peak in HBLs.

Lichti et al. (2008)

Acciari et al. (2009)
Blazar Markarian 421 in Outburst

(a) INTEGRAL/OMC
(b) INTEGRAL/JEM-X
(c) INTEGRAL/ISGRI
(d) Fermi/LAT (0.1–100 GeV)

INTEGRAL Picture of the Month
November 2013
X-Ray Polarimetry

Compton Polarization

Compton cross section is polarization-dependent:

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{4} \left( \frac{\epsilon'}{\epsilon} \right)^2 \left( \frac{\epsilon}{\epsilon'} + \frac{\epsilon'}{\epsilon} - 2 + 4 \left[ \vec{e} \cdot \vec{e}' \right]^2 \right)$$

Thomson regime: $$\epsilon \approx \epsilon'$$

$$\Rightarrow \frac{d\sigma}{d\Omega} = 0 \text{ if } \vec{e} \cdot \vec{e}' = 0$$

$$\Rightarrow$$ Scattering preferentially in the plane perpendicular to $$\vec{e}$$!

Preferred polarization direction is preserved.

$$\epsilon = h\nu/(m_ec^2):$$
X-ray Polarimetry

General idea:

Single Compton Scattering

Look for bi-polar anisotropy of scattered photons

In IBIS:
Single scattering in ISGRI → anisotropic signal in PICsIT.
Crab Nebula / Pulsar:

High degree of polarization (46 ± 10 % at 0.1 – 1 MeV; 72 % at 200 – 800 keV); PA consistent with pulsar jet axis (Dean et al. 2008; Forot et al. 2008)

→ Highly ordered B-field structure and particle outflow.
Claimed very high degree of polarization; controversial:

For GRB 041219A:

SPI: > 90 %
IBIS: 22 – 90 %

Götz et al. (2009)
X-Ray Polarimetry - XRBs

X-Ray Polarization in Cyg X-1 primarily associated with hard (non-thermal) tail
Summary and Outlook

1. INTEGRAL's combined hard X-ray / soft $\gamma$-ray imaging + spectroscopy capabilities remain unparalleled for the near future.

2. Important for
   - $\gamma$-ray line studies (nucleosynthesis; positron annihilation)
   - Obscured HMXBs and AGNs (→ accretion geometry in HMXBs and AGNs; AGN unification; Hard X-ray background)

3. Continuum sensitivity not much better than predecessors; better sensitivity needed for LSP blazars ("MeV blazars"?)

4. X-ray / $\gamma$-ray polarimetry remains a frontier in high-energy studies; several X-ray polarimeter developments underway and proposed for next SMEX.