INTEGRAL observations of $\gamma$-ray polarized sources

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INTEGRAL Scientific payload

OMC (optical)

IBIS
- 15 keV - 10 MeV
- 12' FWHM imaging
- <1' source location
- 19°x19° FOV

JEM-X

SPI
- 20 keV - 8 MeV
- 2 keV FWHM
- 26° Ø FOV

Satellite
- 4.1 tons
- 5 m height
- 3.7 m diameter
- Launched in 2002

ISDC
The IBIS telescope

IBIS detector assembly:
- two stacked detection planes, lateral and bottom veto
- anticoincidence, passive tungsten shield

THE IBIS INSTRUMENT

- Hopper
- CdTe layer (ISGRI)
- CsI layer (PICSIT)
- Veto

Coded mask, placed 3.2m above detector (1m²)

Collection area ~ 3000 cm²

Two-Layers detector:
1) 2mm thick CdTe (ISGRI)
2) 30mm thick CsI (PICSIT)

Field-of-view: ±14.5°FWZR (±4.5°fully coded)
The IBIS/Compton telescope

- The IBIS telescope is a coded mask telescope which could be used as a Compton telescope.
- The Compton mode events are ISGRI and PICSIT events in temporal coincidence, within a window $\tau_W \approx 3.8 \, \mu s$.
- Within this window, chance coincidence, called hereafter “spurious events”, may also occur.
Compton polarimetry principles

- $\pi$-periodic modulation
  - $a = \text{modulation factor}$
  - polar. fraction = $PF = a/a_{100}$
  - $a_{100} = \text{modulation for a 100% polarized source.}$
  - $a_{100}$ between 0.2 and 0.4 for IBIS.
  - $a_{100} = 0.304 \pm 0.003$ for a Crab-like spectrum (MC).
  - polar. angle = $PA = \varphi_0 - \pi/2 + n\pi$

\[ S = \overline{S} \left[ 1 + a \cos(2(\varphi - \varphi_0)) \right] \]
Image deconvolution

200–800 keV T=300 ks

Shadowgram deconvolution

⇒ SOURCE DIRECTION

Integral polarisation observations

February, 17th 2017
Checks for systematics

maximum modulation for unpolarized data?
(square detectors, grids, pixels, mask pattern…)

- strong calibration source
  - at 392, 511, 662 keV
  - $a < 5\text{-}7\ %$
- empty fields
  - $a < 5\ %$
- observations at $\neq$ source-detector angles
  - same results
- spurious event files
  - $a = 15\ %$ @ 180°

Spurious events
Error measurements, probability law

To make error contours, we use the following probability law, which take into account that PA and PF are not independent, and based on Gaussian distributions for the orthogonal Stokes components:

\[
dP(a, \psi) = \frac{N_{pt} S^2}{\pi \sigma_S^2} \exp\left[-\frac{N_{pt} S^2}{2 \sigma_S^2} \left[a^2 + a_0^2 - 2aa_0\cos(2\psi - 2\psi_0)\right]\right] \, da \, d\psi
\]

\[
N(\psi) = S[1 + a_0\cos(2\psi - 2\psi_0)]
\]

Errors on one parameter are given by integrating this law over the other parameter.
Hard X-ray/optical observations of Crab polarisation
Optical and hard-X rays polarimetry study of the Crab system

Observations with the GASP polarimeter and the INTEGRAL/IBIS telescope

1/ Optical observations:
   - 2005 (HST), 2012 (GASP at Palomar)
   - 2015 (GASP at WHT)

2/ Hard X-rays view: INTEGRAL/IBIS
   - calibration and monitoring of Crab with INTEGRAL each six months
HST Polarimetric observation of the Crab Nebula & Pulsar

Observations of nebula with HST/ACS (0, 60 & 120°)
September – December 2005 (Moran et al. 2013)

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Integral polarisation observations
Optical Polarisation with the
Galway Astronomical Stokes Polarimeter (GASP)
(Contact : andy.shearer@nuig.ie)

- Ultra-high speed, Full Stokes, Astronomical Imaging Polarimeter
- Division of Amplitude Polarimeter (DOAP)
- Linear & Circular polarisation
- Studies(~ms) variations in optical pulsars and magnetic CVs

GASP at Palomar (2012)
Optical + Hard X-rays

Integral polarisation observations

Optical values

2005 HST data
\[\Theta = 109.5 \pm 0.7^\circ\]
PF = 7.7 ± 0.1 %
Moran et al, 2013

2012 GASP data
\[\Theta = 85.3 \pm 1.4^\circ\]
PF = 9.6 ± 0.5 %
Moran et al, 2016

2015 GASP data
\[\Theta = 130^\circ\]
(analysis in progress)

INTEGRAL

2003 – 2007 data
\[\Theta = 115 \pm 11^\circ\]
PF = 96 ± 34 %

2012 – 2014 data
\[\Theta = 80 \pm 12^\circ\]
PF = 98 ± 37 %
Moran et al, 2016

end 2015 data
\[\Theta = 125 \pm 15^\circ\]
PF = 89 ± 28 %
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Summary

Blue : Hard X-ray
Red : Optical
Open questions and future work

Change in polarization seen with GASP and Integral

Which origin?

- Magnetic reconnection?
- Time scale of the change (hours, days, week, year?)
- What are the links with high energy flares?
- Where the observed change come from (knot?)

To be continued ⇒ March 2016 campaign:
Astro-H/SGD/HXI + ASTROSAT + INTEGRAL
nearly simultaneous observations

- GASP and Integral: phase resolved analysis
- Integral: regular (2/year) calibration observations
- GASP: Mapping of the optical polarisation of the nebula around the pulsar
  - GASP: new run in 2017 (new camera)
Study of GRB polarisation
Status on INTEGRAL/GAP observation of GRB polarization

Table 3. Summary of recent GRB polarization measurement by IBIS and GAP.

<table>
<thead>
<tr>
<th>GRB</th>
<th>2 (68% c.l.)</th>
<th>Peak energy (keV)</th>
<th>Fluence and Energy Range (erg cm$^{-2}$)</th>
<th>z</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>041291A</td>
<td>65±26%</td>
<td>201$^{+80}_{-41}$</td>
<td>2.5$\times 10^{-4}$ in 20–200 keV</td>
<td>0.31$^{+0.54}_{-0.26}$</td>
<td>IBIS</td>
</tr>
<tr>
<td>06122</td>
<td>&gt;60%</td>
<td>188±17</td>
<td>2.0$\times 10^{-5}$ in 20–200 keV</td>
<td>1.33$^{+0.77}_{-0.76}$</td>
<td>IBIS</td>
</tr>
<tr>
<td>100826A</td>
<td>25±15%</td>
<td>606$^{+134}_{-109}$</td>
<td>3.0$\times 10^{-4}$ in 20 keV–10 MeV</td>
<td>0.71–6.84$^1$</td>
<td>GAP</td>
</tr>
<tr>
<td>110301A</td>
<td>70±22%</td>
<td>107±2</td>
<td>3.6$\times 10^{-5}$ in 10 keV–1 MeV</td>
<td>0.21–1.09$^1$</td>
<td>GAP</td>
</tr>
<tr>
<td>110721</td>
<td>84$^{+16}_{-28}$%</td>
<td>393$^{+199}_{-104}$</td>
<td>3.5 $\times 10^{-4}$ in 10 keV–1 MeV</td>
<td>0.45–3.12$^1$</td>
<td>GAP</td>
</tr>
<tr>
<td>140206A</td>
<td>&gt;48%</td>
<td>98±17</td>
<td>2.0$\times 10^{-5}$ in 15–350 keV</td>
<td>2.739±0.001</td>
<td>IBIS</td>
</tr>
</tbody>
</table>

$^1$ redshift based on empirical prompt emission correlations, not on afterglow observations.

Götz et al, 2014

+ on going study of GRB 161023A …
(also observed by ASTROSAT/CZTI)
GRB 041219A and GRB 140206A
in a few words

GRB 041219A is the longest and brightest GRB detected in the Integral FOV so far …

GRB 140206A is the most distant polarized GRB we observed with INTEGRAL.
We have divided the GRB light curve in 10 s time bins to measure the polarization evolution.
GRB 041219A polarisation temporal variability

<table>
<thead>
<tr>
<th>Name</th>
<th>$T_{\text{start}}$ (UT)</th>
<th>$T_{\text{stop}}$ (UT)</th>
<th>$\Pi$ (%)</th>
<th>P.A. (deg)</th>
<th>Image (SNR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First peak</td>
<td>01:46:22</td>
<td>01:47:40</td>
<td>&lt;4</td>
<td>...</td>
<td>32.0</td>
</tr>
<tr>
<td>Second peak</td>
<td>01:48:12</td>
<td>01:48:52</td>
<td>43 ± 25</td>
<td>38 ± 16</td>
<td>20.0</td>
</tr>
<tr>
<td>P6</td>
<td>01:46:47</td>
<td>01:46:57</td>
<td>22 ± 13</td>
<td>121 ± 17</td>
<td>21.5</td>
</tr>
<tr>
<td>P8</td>
<td>01:46:57</td>
<td>01:27:07</td>
<td>65 ± 26</td>
<td>88 ± 12</td>
<td>15.9</td>
</tr>
<tr>
<td>P9</td>
<td>01:47:02</td>
<td>01:47:12</td>
<td>61 ± 25</td>
<td>105 ± 18</td>
<td>18.2</td>
</tr>
<tr>
<td>P28</td>
<td>01:48:37</td>
<td>01:48:47</td>
<td>42 ± 42</td>
<td>106 ± 37</td>
<td>9.9</td>
</tr>
<tr>
<td>P30</td>
<td>01:48:47</td>
<td>01:48:57</td>
<td>90 ± 36</td>
<td>54 ± 11</td>
<td>11.8</td>
</tr>
</tbody>
</table>

Notes. Errors are given at 1σ c.l. for one parameter of interest.
GRB 140206A polarimetry

20s of data:
Θ = 80 ± 15°
PF > 48 %
GRB 140206A: constraints on LIV

LIV : Lorentz invariance violation

- LIV => differential rotation of the polarization angle.

- Already studied using the SPI measurement of Crab polarization (Maccione et al. 2008), and then with the GRB 141202A measurements (Laurent et al. 2011).

- The further away is the source, the better is the constraint.
GRB 140206A: distance determination

Redshift measure with the TNG telescope (La Palma, Götz et al., 2013):

=> \( z = 2.739 \pm 0.001 \)

=> \( d = 23 \text{ Gpc} \)

with standard cosmological parameters

\( (\Omega_m = 0.27, \Omega_{\Lambda} = 0.73, H = 71 \text{ km/s/Mpc}) \)
GRB 140206A: constraints on LIV

Modification of the light dispersion relation:

\[ \omega^2 = k^2 \pm \frac{2\xi k^3}{M_{Pl}} \equiv \omega_\pm^2. \]

\[ \omega_\pm = |p| \sqrt{1 \pm \frac{2\xi k}{M_{Pl}}} \approx |k|(1 \pm \frac{\xi k}{M_{Pl}}), \]

\[ \Delta \theta(p) = \frac{\omega_+(k) - \omega_-(k)}{2} d \approx \frac{k^2 d}{2M_{Pl}} \xi. \]

M_{Pl}: reduced Planck scale
(2.4 \times 10^{18} \text{ GeV})

\[ \xi < \frac{2M_{Pl} \Delta \theta(k)}{(k_2^2 - k_1^2) d} \]

\[ \xi < 10^{-16} \]

Götz et al, 2014
Polarisation of X-ray binaries
Cygnus X-1
Cygnus X-1 observations log

- We have taken Cygnus X-1 observation from 2003 to 2012 (Rodriguez et al. 2015).

- We have summed all IBIS data along given Cygnus X-1 spectral states (LHS, IS and HSS).

- Indeed, we previously developed a method to classify the states of Cygnus X-1 at any given time based on hardness and intensity measurements with the RXTE/ASM and MAXI and on the hard X-ray flux obtained with the Swift/BAT (Grinberg et al. 2013).
Cygnus X-1 high energy spectrum

Two spectral components:

- **20-400 keV**
  - Thermal Comptonisation
  - $kT = 53 \pm 2$ keV
  - $\tau = 1.15 \pm 0.04$

- **400 - 2000 keV**
  - Power-law:
  - $\text{index} = 1.4 \pm 0.3$

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Rodriguez et al., 2015

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Cygnus X-1 polarisation (400 - 2000 keV)

2 Ms of data (LHS):
\[ \Theta = 40 \pm 15^\circ \]
\[ \text{PF} = 67 \pm 30 \% \]

1.2 Ms of data (HSS):
No detection
\[ \text{PF} < 70 \% \]

Rodriguez et al., 2015

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V 404 Cygni
V404 Cygni Compton light curves (32s; rev. 1555)

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Integral polarisation observations
V 404 Cygni polarisation (450 - 2000 keV)

June 2015
149 ks of data:
Θ = 160 ± 15°
PF = 95 ± 35%

PRELIMINARY !!!
V 404 Cygni polarisation 
($\gamma$-ray vs optical/NIR)

June 2015
149 ks of data:
$\Theta = 160 \pm 15^\circ$
PF = 95 $\pm$ 35%

$\Theta = 171^\circ$

NIR (Shahbaz et al. 2016)
Conclusion

- The measure of polarization in hard-X/soft-gamma rays is a powerful tool to investigate the emission mechanisms and geometry of high-energy astrophysical sources.

- Fundamental physics questions can also be addressed (constraints on Lorentz Invariance Violation).

- Joint observations with ASTROSAT/CZTI are planned, and discussion are on-going with the POLAR team.
THANK YOU !!