Lorenzo Natalucci
for the IACHEC Non-thermal SNR Working Group
Report Fall 2021
Current WG e-mail list

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If interested to join, please contact: lorenzo.natalucci@inaf.it
It mainly aims at the cross-calibration analysis of G21.5-0.9 (mainly below 10 keV) and of the Crab spectra (mainly above 10 keV).

- Define a reference model for cross-calibration in the energy band from soft X-rays to hard X-rays
- Analyse observational data in the context of cross-calibration. Extract ratios for instrument renormalisation in different energy bands

The WG started its activities in 2007 (Lake Arrowhead). Initial chairperson: Manabu Ishida

An important milestone is reached in 2010 (chairperson: M.Tsujimoto) with publication of cross-cal paper on G21.5-0.9

Preliminary discussion on: PSR B1509-58, the pulsar in the «Hand-of-God» SNR
Updates since May

- Major calibration updates from NuSTAR and INTEGRAL/ISGRI
- New calibration of NICER using Crab raster observations. Progress in NuSTAR/Nicer comparison?
- Updated Crab dataset
- Discussion about to start a new project based on Crab pulsed spectrum (what missions?)
- G21.5-0.9 calibration model: planning more work to analyse multi-mission data. Need to kickoff a sub-group
- Forthcoming cross-cal project on PSRB1509-58
**G21.5-0.9**

- Compact plerionic nebula, routinely observed in the X-ray band (typically 0.1-10 keV). Faint in the hard X-rays (~mCrab)

- Important calibration source for all X-ray instruments including future missions (XRISM, Athena,... more)

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**NuSTAR**

**Nynka+15**

**Image size: 8’**

**Warwick+01**

**Hitomi**

$E_{\text{break}} = 7.1 \pm 0.3 \text{ keV}, \Gamma_{\text{soft}} = 1.74 \pm 0.02, \Gamma_{\text{hard}} = 2.14 \pm 0.01$
**G21.5-0.9 cross-cal paper**

In the soft X-ray band, results are broadly consistent with other measurements (e.g. 3C273).

Different situation for the hard band: for example, PIN/ISGRI flux ratio=1.3 but for the Crab we find ~10-12%
G21.5

• We had one paper on this (Tsujimoto+11)

• Motivations for a new paper.
  – New data accumulated: NuSTAR, Hitomi, INTEGRAL, etc.
  – New calibration results. e.g., Hard-band response (8-12 keV) improved for XIS0,3.
  – New model (Energy break)

• We can prepare a new paper with a focus on >~5 keV range.

IACHEC 2017 – Lake Arrowhead
The Crab multi-mission project

- Results exclusively based on the analysis of nearly simultaneous periods
- Emphasis on the hard band (>10 keV)
- Instruments already on board: XIS, PIN, GSO, PCA, IBIS/ISGRI, SPI, NuSTAR, (EPIC-pn), GBM, BAT, ASTROSAT/CZTI (new)
- Broken power law model, with $E_{br} \sim 100$ keV
- Broad band spectral fitting: energy range is essentially the operative range of the instrument

<table>
<thead>
<tr>
<th>Instr.</th>
<th>Energy Bands (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XIS</td>
<td>3–10</td>
</tr>
<tr>
<td>PIN</td>
<td>10–25, 25–80</td>
</tr>
<tr>
<td>GSO</td>
<td>25–80^ 100–300</td>
</tr>
<tr>
<td>PCA</td>
<td>3–10, 10–25, 25–80</td>
</tr>
<tr>
<td>IBIS</td>
<td>25–80, 100–300</td>
</tr>
<tr>
<td>SPI</td>
<td>25–80, 100–300</td>
</tr>
<tr>
<td>NuSTAR</td>
<td>3–10, 10–25, 25–80</td>
</tr>
<tr>
<td>EPIC</td>
<td>3–10</td>
</tr>
<tr>
<td>GBM</td>
<td>(25–80), 100–300</td>
</tr>
<tr>
<td>BAT</td>
<td>25–80</td>
</tr>
</tbody>
</table>

^for GSO, E >40 keV
Flux history 25-80 keV

PCA
PIN
Nustar
Astrosat/CZTI
SPI
ISGRI
BAT
★ = calibration update
Spectral slope ($\Gamma, E< E_{\text{break}}$)

PCA  
XIS  
PIN  
NuSTAR  
Astrosat/CZTI  
SPI  
ISGRI  
BAT

$\star$ = calibration update
Crab & instruments calibration
New reports
NuSTAR Calibration Update

Kristin K. Madsen & Brian Grefenstette
And the NuSTAR SoC
2012 In-flight Calibration

• Implemented a 15% increase in effective area to decrease the flux

• Focused Crab model:
  • Gamma = 2.1
  • N = 8.5
Instrument components

- MLI cover *
- Multilayer Optic
- MLI cover
- Be window*
- Detector absorption layer
- CZT Detector

ARF

Stray-light data

* Presumed constant
ARF fitting

Off-axis distribution from individual observations

Original Vignetting

Counts

0 - 1'
1 - 2'
2 - 3'
3 - 4'
4 - 5'
5 - 6'
6 - 7'

Total Counts

Off axis angle (arcseconds)

FPMA
FPMB

11/9/21
71 focused Crab observations
Relative model components
Table 7. Mean and standard deviation of all focused Crab observations between 1′–4′.

<table>
<thead>
<tr>
<th>Module</th>
<th>$\Gamma$</th>
<th>Normalization (keV$^{-1}$ cm$^{-2}$ s$^{-1}$)</th>
<th>Flux (3–10 keV) ($10^{-8}$ ergs cm$^{-2}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crab$^\dagger$</td>
<td>2.1</td>
<td>8.5</td>
<td>1.38</td>
</tr>
<tr>
<td>FPMA</td>
<td>2.097 ± 0.023</td>
<td>8.74 ± 0.44</td>
<td>1.42 ± 0.033</td>
</tr>
<tr>
<td>FPMB</td>
<td>2.103 ± 0.033</td>
<td>9.20 ± 0.71</td>
<td>1.49 ± 0.042</td>
</tr>
<tr>
<td>ARF v007</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crab$^\dagger$</td>
<td>2.013</td>
<td>9.69</td>
<td>1.57</td>
</tr>
<tr>
<td>FPMA</td>
<td>2.104 ± 0.013</td>
<td>9.66 ± 0.23</td>
<td>1.56 ± 0.026</td>
</tr>
<tr>
<td>FPMB</td>
<td>2.105 ± 0.009</td>
<td>9.68 ± 0.19</td>
<td>1.56 ± 0.028</td>
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<tr>
<td>ARF v008</td>
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$^\dagger$ Canonical Crab values used for the calibration.
Major NICER calibration update released July 2021
Addition of response matrix calculator tasks (nicerarf & nicerrmf) versus to pre-calculated responses
Based on analysis of existing NICER Crab raster observations
  - Ray-tracing data
  - Tip-tilt & boresight misalignment of optics included
Capability for off-axis and diffuse targets
NICER Crab Performance

- Kaastr et al 2009 Nebula + Pulsar model
- Crab residuals <1.5% over 0.4-10 keV range
- No strong residual features at known astrophysical / detector positions
• NICER has used Kaastra et al’s (2009) model
  \[ \text{tbvarabs*xscat(curv*powerlaw + crab_pulsar)} \]
• Crab pulsar model based upon Kuiper et al (2001), which combines BeppoSAX LECS (>0.1 keV), MECS & PDS as well as Compton GRO
  \[ F_p = 726E^{-1.276}e^{-0.074x^2} + 1464E^{-1.165}e^{-0.159x^2} + 2021E^{-2.022} \]
• NICER uses this pulsar model “as-is” with no change; NuSTAR??

LEFT: NICER Crab model applied as-is on NuSTAR SL. No fitting.

RIGHT: pulsar norm = 0 then we can agree on the the slope and the ratio between NuSTAR/model \sim 1.065.

Is pulsar component right? Worth looking at pulsed spectrum?
OSA11.2-beta: ISGRI

Volodymyr Savchenko

Sardinia, October 14 2021
OSA10 issues

- Spectra of one or two bright sources quite different from Crab are not reconstructed correctly
- Big discrepancies after ~2017, hard or impossible to correct with OSA10 approach (ad-hoc efficiency, fitting ARF)
- Line positions of some cyclotron line sources, Her X-1 sometimes (rarely) mismatch strongly
- Presumably, ARF should represent effective area, not electronic issues.
  - ISGRI Efficiency: from detected events to reconstructed rates (done by OSA internally)
  - RMF+ARF: from reconstructed rate to flux (done in expect out of OSA)
- Long-term reconstructed rate stability (e.g. Crab)
- Can we understand ISGRI detector, and make physical, continuous model at least for some parts? This should make spectra smoother, predictions more absolute.
- Understand detector polarization, fast (~several hours) and historic
Calibration
Fit charge loss model to background

OSA
Reconstruct deposited “photon” energies
Reconstruct “equivalent” count rates dividing by efficiency
Fit detector plane with model shadows

Verification
No ARF fitting for now (even if it’s not necessarily a bad thing)
Fitting spectra (xspec)

GEANT
Fit low-energy RMF and efficiency

3ML
Multi-Mission Maximum Likelihood Framework
Verification machinery

Jupyter notebooks with extra annotations: conventional “modern” technologies, ready to be public. Only concern is data rights for some workflows/results.

Can be run on one of numerous compatible platforms: binder, googlecollab, Renku (EPFL), DataLabs (ESA)

Can also fetch other data sources, especially web-based analysis (INTEGRAL and not).

Pluggable, fetching and fitting parts can be replaced.

Is run automatically in response to new OSA or data.
Aggregated results: High-energy reconstruction and flux

Differences in reconstructed parameters between ISGRI and “expectations”
Long-term count rate: Crab

above ~60 keV - “absolute” measurement with detector model. Below - using efficiency instead of ARF.
Ready?

No more anomalous source features (see 1A 0535+105), background spectra look the same **OK**

Cyclotron line sources consistent with reference where available **OK**

High-energy (>60 keV) rates stable from physical detector model **OK**

ARF does not change, efficiency and RMF do **OK**

*Internal (to IBIS team) validation beta ready in MMODA and normal IC.*

ISGRI still evolving. Need to follow until the end of the mission. **ok for now**

Rapid evolution caused by polarization is implemented, but not available in the beta. **ok for now**

Detector plane background model should be updated. **ok for now**
Calibration with PSR B1509-58/MSH 15-52
(James Rodi, INAF/IAPS)

• Period of ~150 ms
• Radio Pulsar detected up TeV
• Observed by instruments from X-ray to gamma-ray
  • RXTE, XMM, HXMT, NuSTAR, INTEGRAL. Suzaku, and other missions
• Good source for both timing and flux calibration since pulsed flux is ~constant
• G21.5-0.9 cross-calibration IACHEC work by Tsujimoto et al (2011)
Some Previous results

- Livingstone & KASPI (2011) ~7yrs of PCA
  - Pulsed flux roughly constant
- Forot et al (2006) ~ 1.3 Ms of ISGRI
- NuSTAR obs from Chen et al. (2016)
- Early work with INTEGRAL/ISGRI with a few observations; have ~12 Ms
Summary

• Activity of WG continues to be focused on Crab and G21.5: good primary standards also for new missions
• NuSTAR new CALDB issued; INTEGRAL/ISGRI new OSA release to be implemented in the Crab dataset; possibly include new epochs & instruments
• New studies of G21.5 model (currently in stand-by): data analysis for Chandra, XMM, NuSTAR, Hitomi, INTEGRAL, Swift for new project.

To follow (actions):
• Crab dataset: include Hitomi Crab spectra for 2016 & investigate more recent epochs
• Advanced draft of Crab paper before IACHEC 2020
• G21.5-0.9: Kickoff meeting to be called soon
Thank you!