International Astronomical Consortium for High-Energy Calibration

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Summary of the 2013 IACHEC Meeting

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Abstract

We present the main results of the 8th International Astronomical Consortium for High Energy Calibration (IACHEC) meeting, held in Theddingworth, Leicestershire, between March 25 and 28, 2013. Over 50 scientists directly involved in the calibration of operational and future high-energy missions gathered during 3.5 days to discuss the status of the X-ray payload inter-calibration, as well as possible ways to improve it. Sect. 4 of this Report summarises our current understanding of the energy-dependent inter-calibration status.

1 The IACHEC

The International Astronomical Consortium for High Energy Calibration (IACHEC)\textsuperscript{\textsuperscript{\textsuperscript{\textsuperscript{[1]}}} is a group dedicated to supporting the cross-calibration environment of high energy astrophysics missions with the ultimate goal of maximising their scientific return. Its members are drawn from instrument teams, international and national space agencies and other scientists with an interest in calibration in this area. Representatives of over a dozen current and future missions regularly contribute to the IACHEC activities. Support for the IACHEC in the form of travel costs for the participating members is generously provided by the relevant funding agencies.

\textsuperscript{[1]}\url{http://web.mit.edu/iachec/}
IACHEC members cooperate within working groups to define calibration standards and procedures. The scope of these groups is primarily a practical one: a set of data and results (eventually published in refereed journals) will be the outcome of a coordinated and standardised analysis of reference sources (“high-energy standard candles”). Past, present and future high-energy missions can use these results as a calibration reference.

The IACHEC meets yearly to report on the progress of the working groups and define the next year’s activities. The inaugural IACHEC meeting was held in 2006 on neutral ground in Iceland, but since then has been hosted by local IACHEC members in Europe, the United States or Asia. In 2013 the 8th IACHEC meeting was held in the United Kingdom at the Hothorpe Hall conference centre in Theddingworth, Leicestershire. The meeting was hosted by the Leicester University XMM-Newton EPIC instrument team.

The format of the IACHEC meetings includes both plenary sessions where instrument calibration status, working group summaries and other topics of interest are presented and parallel splinter sessions where working groups meet to discuss results and use the opportunity for face-to-face data analysis sessions.

This Report summarises the main results of the 8th meeting. It is organised as follows: Sect. 2 describes the main results discussed by each of the Working Groups. Sect. 3 summarises a discussion good statistical practises in analysing calibration data. Sect. 4 summarises the cross-calibration status. For more details, readers are referred to the presentations collected at the IACHEC meeting web page: [http://web.mit.edu/iachec/meetings/2013/index.html](http://web.mit.edu/iachec/meetings/2013/index.html)

# 2 Working Group reports

The scope of the IACHEC Working Groups\footnote{http://web.mit.edu/iachec/wgs/index.html} is to define standard procedures for the calibration of high-energy instrumentation in specific areas, such as: methodology, definition of calibration targets, and requirements for future missions.

Particular emphasis is addressed to the definition of a set of “high-energy standard candles”, which can be used as reference for the calibration of past, present and future X-ray instruments. Each type of standard candle is intended to optimally address a specific parameter sub-space in the energy or timing domain. In this framework, the scope of these working groups is:

- to agree on a “standard spectral model” for each of the high-energy standard candles
- to maintain a database of cross-calibration results on the high-energy standard candles
- to maintain a database of standard candle spectral data, through which any high-energy astronomers will be able to reproduce and gain confidence on the results produced by the IACHEC Working Groups
2.1 CCD

The CCD Working Group continued its history of providing a forum for cross-mission discussion and comparison of CCD-specific modelling and calibration issues. At IACHEC 2013, we heard talks about Suzaku/XIS, Chandra/ACIS, XMM-Newton/EPIC-pn and Swift/XRT on a variety of issues.

To begin with, we heard about the particle background characterisation efforts on Chandra/ACIS and Suzaku/XIS, specifically, the spatial structure as a function of energy on Chandra/ACIS, and the time evolution at low and high-energies on Suzaku. There was interest in having all missions/instruments provide standard background models or templates, so users can more easily include a background model in their spectral fits.

Matteo Guainazzi described the new energy scale calibration for XMM-Newton/EPIC-pn in timing mode that will be released shortly as part of SAS 13. This calibration includes rate-dependent effects and correction for X-ray loading seen when the bright source contaminates the offset map. He also proposed future coordinated observations of a bright X-ray binary by multiple missions in their own timing modes to better understand the pulse height redistribution differences between standard and timing modes.

Claudio Pagani described the Swift/XRT effort to characterise and map charge traps both in the flight device and in laboratory irradiation tests. The Swift/XRT is unique among the IACHEC CCD instruments in that they have developed deep (10-100 eV) traps since launch. There was some speculation as to the cause. CTI correction software does an excellent job of mitigating most of the lost performance.

Finally, there was a group discussion of how to manage calibration of long duration missions when our favourite calibration source (Fe-55) has a half-life of only 2.73 years. Astrophysical sources can replace some of the functionality, as can instrumental features or background lines, if they interact in the same manner as astrophysical X-rays. Continual monitoring of gain evolution, for example, may either need to be less accurate, or may require more calibration time. Astro-H will carry a Modulated X-ray Source which will produce multiple spectral lines with no radioactive decay. We eagerly await reports of the on-orbit performance of this device.

2.2 Galaxy Clusters

Since clusters of galaxies are stable over human time-scales, and (the nearest ones) have high X-ray brightness and hard spectra, they are useful standard candles for X-ray calibration. Thus, one does not have to observe them simultaneously for cross-calibration purposes, which allows the usage of archived (non-simultaneous) data to form large samples. We extended our previous sample of 11 clusters (Nevalainen et al., 2010) to ~60 clusters from the HIFLUGCS sample for a comparison of XMM-Newton/EPIC and Chandra/ACIS instruments. The results of this work are preliminary but seem to be in line with those published earlier.

We published our results on cross-calibration of the XIS instruments on-board Suzaku satellite using clusters of galaxies (Kettula et al. 2013: Fig. [4]). The 2–7 keV band yields temperatures consistent with EPIC-pn instrument on-board XMM-Newton satellite. The cluster temperatures in
Figure 1: Average relative difference (diamonds), the error of the mean of the temperatures (solid line) and fluxes (dotted line) using the public calibration in the soft band (left side of the plot) and in the hard band (right side of the plot). Comparison of the XMM-Newton/EPIC-pn and Suzaku/XIS soft band temperatures using the modification to the contaminant in the latter is shown with green diamonds and dashed lines. Figure after Kettula et al., 2013

the 2–7 keV band as measured by XMM-Newton/EPIC-pn have previously been shown to be consistent with those obtained with XMM-Newton/EPIC-MOS, Chandra/ACIS and BeppoSAX/MECS instruments (Nevalainen et al. 2010). Additionally, the continuum-based bremsstrahlung temperature measurements agree with the ionisation temperatures obtained from Fe XXV/XXVI line flux ratio measurement performed using XMM-Newton/EPIC data. Thus, there is a wide consensus on the accurate effective area calibration among XMM-Newton/EPIC, Chandra/ACIS, Suzaku/XIS and BeppoSAX/MECS instruments in their hardest energy band.

At the lower energies (0.5–2.0 keV) there are significant cross-calibration discrepancies. We have been experimenting with using constraints of cluster physics obtained from other wavelengths, e.g. the thermal pressure via Sunyaev-Zeldovich effect and total cluster mass via gravitational lensing, to compare with equivalent quantities derived from X-rays. The aim is to find a consensus between the maximal number of physical processes and wavelengths to judge, which one(s) of the X-ray missions may have larger uncertainties in the calibration of the effective area. Results are still inconclusive.

We have started a project aiming at comparing the spectroscopic results for a sample of clusters of galaxies obtained with XMM-Newton/EPIC, Chandra/ACIS, Suzaku/XIS, Swift/XRT and ROSAT/PSPC instruments. The preliminary results indicate that this study will be useful in assessing the uncertainties of the effective area calibration.

Recently we have started a collaboration with the NuSTAR team in order to observe some of the clusters already studied in our earlier projects. We are conducting feasibility studies for the
observations which will be useful for planning new observations.

2.3 High-resolution

The objectives of the High-Resolution Working Group are fourfold: to identify all the lines in the X-ray spectrum first of Capella and later of a small number of reference objects; feed measured line wavelengths and intensities back to atomic databases; test equilibrium plasma models; and establish X-ray wavelength standards for calibration purposes. The first spectrum to be addressed is the combined Chandra HETG spectrum of Capella, using both MEG and HEG spectra. The line lists are based on a decomposition of ATOMDB models into their various line and continuum components, comprising electric and magnetic dipole and quadrupole or EM transitions; dielectronic recombination or DR transitions; two-photon continua and radiative-recombination continua, all of which involve bounds states of ions; and electron continuum emission. It has been agreed to build models for all 1494 EM lines with a peak emissivity above $10^{-19}$ photons cm$^{-3}$ s$^{-1}$.

2.4 Non-Thermal SNRs

The Non-Thermal SNR Working Group is fostering cross-calibration activities using spectra of known “Non-Thermal” Supernova Remnants like G21.5-0.9, the Crab, and PSR 1509-58. A reference paper on G21.5-0.9 was published in the recent past (Tsujimoto et al. 2010) and a cross-calibration project based on X-ray observations of the Crab Nebula is ongoing.

This year the NuSTAR team has joined the Working Group effort and during the splinter meetings held at this IACHEC Conference a detailed view of the NuSTAR calibration status has been given (K. Madsen). Modelling the Crab Nebula spectrum with a simple power-law in the NuSTAR energy band (4–80 keV), the residuals are at most within a few percent of the convolved model. This is a good result considering the early mission phase. In order to achieve a good absolute accuracy an empirical correction of the effective area on Crab spectra could be necessary in the short term. A discussion on this issue followed with the basic aim to feed the NuSTAR team with as much information as possible on the Suzaku and INTEGRAL results. L. Natalucci has presented the status of the Crab cross-calibration project with the detailed list of available observations, with data provided by the Suzaku, RXTE, INTEGRAL and XMM-Newton teams. In order to cope with the source variability a set of 6 nearly simultaneous epochs (now being updated to 7) have been identified on the basis of the available data-sets.

The preliminary results on the Crab analysis, mostly based on spectra averaged on a long term period (2005-2011), confirm the picture that emerged in the Tsujimoto et al. paper, in terms of normalisation difference between Suzaku/HXD, RXTE/PCA and INTEGRAL/IBIS-ISGRI instruments. More data from INTEGRAL/SPI will be available soon (E. Jourdain) and possibly from Fermi/GBM (G. Case). Y. Terada presented recent results on Crab PWN with Suzaku/HXD (Kouzu et al. 2013) indicating spectral variations in the hard X-ray band as well as X-ray flux. The advantages of global modelling via a curved power-law instead of a broken power-law were also discussed. The use of spectral indices in any given band could be more robust because the slope doesn’t change discontinuously. Therefore, comparing fluxes in some pre-defined bandpass for simple power-law
model fits could be a valid approach.

Concerning G21.5-0.9, we have pointed out that it makes perfect sense to update the above cited paper with all the additional data from other missions and adding the NuSTAR data, in order to see if there is evolution and improvements in the cross calibration. L. Natalucci presented long-term IBIS/ISGRI spectra showing a remarkable stability over the years, characterised by \( F(15 - 50 \text{ keV}) = (3.95 \pm 0.24) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \) and power law index \( \Gamma = 2.05 \pm 0.13 \).

Finally, a discussion emerged about using PSR B1509-58 (the Pulsar in G320.401.2, also known as the Hand of God) as a new high energy calibration source. Suzaku, as reported by Y. Terada looked at this source during their first light and is using this as a timing calibrator (Terada et al. 2008). Possibly the future high energy observatories from China (HMXT) and India (Astrosat) will use it as a calibration target as well. NuSTAR has plans to observe it as a science target and Suzaku team could be very interested in joining in looking at it. However, it is under discussion whether PSR B1509-58 could be used for calibration of NuSTAR due to contamination by the nearby diffuse X-rays.

For the DAMPE team, J. Li has expressed interest in possible future projects involving higher energy, i.e. gamma-rays in the Fermi band (\( \leq 300 \text{ GeV} \)). An effort for this to get started in the coming years is envisaged.

### 2.5 Thermal SNRs

Work at previous IACHEC meetings has led to the development of a standard model for the SMC SNR 1E 0102.2-7219 (E0102 hereafter), which has been described in two SPIE papers (Plucinsky et al. 2008, 2012). This standard E0102 model has become a valuable tool for the various calibration teams to understand time-dependent changes in their respective instrument responses. This model has been used to characterise changes in the XMM-Newton/EPIC-MOS1 and XMM-Newton/EPIC-MOS2 responses, to monitor the growth of the contamination layer on the ACIS filter, to develop the contamination model for the Suzaku/XIS, and to modify the CCD electrode transmission model for the XRT. The XMM-Newton/EPIC-pn instrument appears to be the most stable instrument, based on the consistency of the observed E0102 count rates over the course of the XMM-Newton mission. We compared the fitted normalisations of the OVII triplet, the OVIII Lyα line, the NeIX triplet, and the NeX Lyα line in order to compare the absolute effective areas of the various instruments at these energies. Fig. 2 shows these results relative to the standard IACHEC model using the latest calibrations or proposed updates to the calibration, with black for the OVII triplet, red for the OVIII Lyα line, green for the NeIX triplet, and the blue for the NeX Lyα line (if a global normalisation for the model spectrum was used, it is shown in purple). It should be emphasised that the IACHEC model is a useful reference model but it should not be considered the truth since it was developed based on the XMM-Newton/RGS and Chandra/HETG calibrations at the time of creation. This comparison shows that most of the instruments agree to within \( \pm 10\% \), with a few exceptions.

The group also continued work on the development of a standard model for the LMC SNR N132D, the brightest SNR in the LMC. N132D’s spectrum is considerably more complicated than E0102’s due to the strong Fe-L shell emission. Nevertheless, a prototype standard IACHEC model
Figure 2: Ratio of the OVII triplet (black), OVIII Lyα (red), NeIX triplet (green), and NeX Lyα (blue) line normalisations, as well as a global normalisation factor (purple), when the IACHEC model is applied to the E0102 spectra of different missions.

has been developed based on the lines identified in the XMM-Newton/RGS and EPIC-pn spectra. This model was compared to the data from the other CCD instruments and some minor revisions to add weaker lines at energies outside the XMM-Newton/RGS bandpass will be needed. The group will work on this revised model over the coming months.

3 IACHEC Statistical Methods

All conclusions regarding values and uncertainties of the physical parameters that encapsulate instruments for calibration purposes and the cosmos at large for more purely scientific work come from the comparison of data and models. Essentially all high-energy instruments currently and recently in operation accumulate individual photon events and are thus described by Poisson statistics. For this reason, the IACHEC community recommends and has adopted the C-Statistic rigorous implementation of the Poisson-likelihood for exploration of parameter spaces rather than any of the alternative Gaussian approximations. A choice needs to be made because of differences in model values inferred with different methodologies. In many cases, the Poisson-likelihood does not suffer the biases that compromise Gaussian methods.

Analysis typically involves simultaneous use of two observed spectra, both subject to Poisson statistics: one combining source and background; the other from the background only. C-Statistic analysis provides the most reliable means for constructing models through parameter-space exploration, subject to a variety of constraints. These methods would benefit from the provision by calibration teams of background models to improve and constrain the implicit phenomenological
back ground methods in regular use. Parameter-space exploration and goodness-of-fit are independent procedures: the Pearson statistic with model variances provides a reliable goodness-of-fit measure for all Poisson model values greater than zero. In this overall scheme, rebinning is not relevant and therefore always to be avoided for the loss of information incurred.

Statistical topics have been the subject of regular discussion at IACHEC meetings. This year’s 8th meeting enjoyed the benefit of a presentation by David van Dyk, Professor of Statistics at Imperial College London, who described Bayesian methods for quantifying effects of calibration uncertainties on scientific analysis. His talk was followed by round-table discussion exploring a number of topics, some of which were not resolved. An IACHEC Statistics Working Group is to be established without delay to encourage best statistical practice as a complement to the standard physical models in widespread use in the high-energy calibration community. Details will be found on the IACHEC web pages shortly.

4 Summary of the cross-calibration status

In this Section, we summarise the status of inter-calibration among operational instruments in three energy bands: “soft” (photon energy, \(E \leq 2\) keV), “medium” (\(E \approx 2–10\) keV), and “hard” (\(E > 10\) keV).

Soft: energy-dependent cross-calibration discrepancies in this energy band were reported by Nevalainen et al. (2010) in the framework of their study of a sample of bright, nearby Galaxy Clusters observed by Chandra and XMM-Newton. Recent results confirm that the ratio between the Chandra/ACIS and XMM-Newton/EPIC-pn fluxes increase from -10\% to +10\% going from 0.5 to 2 keV\(^3\). A similar behaviour is observed when comparing Swift/XRT and XMM-Newton/EPIC-pn. On the other hand, the flux ratio between the Suzaku/XRT and XMM-Newton/EPIC-pn cameras is energy-independent, and comprised between -5\% and -10\% (Kettula et al. 2013). XMM-Newton/EPIC-MOS cameras yield fluxes which are on the average in good agreement with EPIC-pn\(^4\), although the exact value in a given observation depends on the calibration of time-dependent EPIC-MOS redistribution and contamination, which is still being refined. The accuracy in the description of contaminants in Chandra/ACIS, Suzaku/XIS, and Swift/XRT is also crucial. Significant improvements have been recently achieved in these areas. However, more work is required to achieve an overall cross-calibration level better than 10\%, as well as to ensure an accurate description of future evolutions of the contaminants’ depth and (possibly) composition. The comparison of the line normalisation in the multi-mission study of the thermal SNR 1E0102-72, upon which many contamination studies have been primarily based, already shows an agreement within ±10\% (Plucinsky et al. 2012\(^5\)).

Medium: Extending the original study by Nevalainen et al. (2010) to a sample of over 60 galaxy clusters in the HI-FLUGCS sample confirms an excellent agreement between the temperatures measured by the Chandra/ACIS and the XMM-Newton/EPIC (within a few percent over the whole range between \(kT \approx 2\) to \(\approx 8\) keV\(^6\)). Suzaku/XIS cameras yield slightly lower temperature (by \(\approx 5\%\); Kettula et al., 2013).

\(^3\)cf. [http://web.mit.edu/iachec/meetings/2013/Presentations/Nevalainen.pdf](http://web.mit.edu/iachec/meetings/2013/Presentations/Nevalainen.pdf)
\(^4\)cf. [http://web.mit.edu/iachec/meetings/2013/Presentations/Read.pptx](http://web.mit.edu/iachec/meetings/2013/Presentations/Read.pptx)
\(^5\)cf. also [http://web.mit.edu/iachec/meetings/2013/Presentations/Thermal_SNR.pdf](http://web.mit.edu/iachec/meetings/2013/Presentations/Thermal_SNR.pdf)
\(^6\)cf. [http://web.mit.edu/iachec/meetings/2013/Presentations/Schellenberger.pdf](http://web.mit.edu/iachec/meetings/2013/Presentations/Schellenberger.pdf)
**Hard**: Recent work on the Crab Nebula confirms the results published in Tsujimoto et al. (2011) on G21.5-0.9. 20–100 keV fluxes measured by Suzaku/HXD, INTEGRAL/IBIS-ISGRI, INTEGRAL/SPI, and RXTE/PCA are within ±6%. Swift/BAT yields fluxes ≃20% lower than INTEGRAL/SPI. Spectral indices are in excellent agreement (±0.04). Preliminary NuSTAR calibrations also yields fluxes in agreement within a few percent when compared to Suzaku. A residual difference in spectral shape (at a level ≤0.04) is expected to be cured with the next release of NuSTAR effective area files, to which an empirical correction based on observations of the Crab Nebula will be applied.

**References**

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<sup>7</sup>cf. [http://web.mit.edu/iachec/meetings/2013/Presentations/Walton.pdf](http://web.mit.edu/iachec/meetings/2013/Presentations/Walton.pdf)

<sup>8</sup>cf. [http://web.mit.edu/iachec/meetings/2013/Presentations/Mardsen.pdf](http://web.mit.edu/iachec/meetings/2013/Presentations/Mardsen.pdf)

<sup>9</sup>see [http://web.mit.edu/iachec/papers/index.html](http://web.mit.edu/iachec/papers/index.html) for a complete list of IACHEC papers