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Absolute flux measurements with INTEGRAL IBIS/ISGRI

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Since the launch of INTEGRAL, the spectral response of ISGRI has been continuously changing under the effect of the cosmic ray irradiation. Up to now, this drift was adjusted with a phenomeological law to make the spectra at different time compatible. The response was generated in order make the Crab pulsar spectrum compatible with SPI observation. We developed a new method of energy calibration based on time-dependent physical model of the instrument. We modelled propagation of charge carriers in ISGRI pixels, computing charge loss depending on microscopic parameters of the detector medium (charge carrier mobility and lifetime). Evolution of these parameters with time, casued by accumulated dose of the cosmic ray radiation, is measured by fitting instrumental background lines. First preliminary application of this approach results in significantly improved source spectra. We show that for the first time, ISGRI spectra can be correctly reconstructed independently of the assumption of the source shape, greatly enhancing the capabilities of ISGRI for studying complex spectra and narrow spectral features. At the same time, our model of detector evolution predicts evolution of the detector efficiecy with time, allowing to perform absolute measurement of the source fluxes. Extensive observations performed with ISGRI on the Crab pulsar over 12 years of INTEGRAL operation allow to study Crab nebula flux evolution with high signal-to-noise ratio and to constrain the high energy spectral evolution. We show that the new results substantially improve the consistency of IBIS/ISGRI derived fluxes and spectra with observations of other hard X-ray instruments.

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1. Introduction

The Crab pulsar and its surrounding wind nebula are among the brightest sources in the sky from the radio domain up to nearly PeV energies [1]. Due to its brightness, the apparent stability and consistent simplicity of the featureless non-thermal powerlaw spectrum it is routinely used as a reference source to calibrate and verify performance of both ground-based and space-based instruments. With the advance in observing technology and accumulation of data it has been discovered that this standard candle can demonstrate rather non-standard behaviour. Very surprisingly, hour-scale flares, comparable to the total pulsar spindown power were observed in the GeV range by AGILE and Fermi/LAT [2, 3]. It is most likely hat these flares originate from the nebula, but the physical process responsible for them remains uncertain. While rapid variability within small structures of the nebula had been detected in X-ray, optical and radio observations, they account only for a small relative change in the total flux of about 1% [1]. This is smaller than typical systematic errors of X-ray instruments, and the Crab was especially frequently used for instrument cross-calibration in this energy range. So it came as a big surprise when a synthetic study of Crab lightcurves using a collection of hard X-ray instruments (Swift/BAT, Suzaku/HXD, Fermi/GBM and INTEGRAL) revealed variability of the total nebula flux in the energy range 20-200 keV as large as 7% [4] over a timescale of several hundred days. Then, possible spectral evolution was observed in the nebula flux by Suzaku/PIN [5].

The coded mask imager IBIS/ISGRI onboard the INTEGRAL space observatory is one of the most sensitive instruments in the energy range from 20 to 900 keV. While focusing hard X-ray instruments, such as NuSTAR [6] perform better in deep observations of dedicated small fields, ISGRI has no match in grasping large field of view with sufficiently good angular resolution and effective area. In one INTEGRAL revolution of the Crab observations it can reach a statistical accuracy of the flux measurement of the order of 0.1%. On the other hand, systematic uncertainties of the flux measurement are large. The primary reason for the bias in flux measurement is the difficulty to perform a precise ISGRI energy calibration.

2. Update in the energy calibration

Low-energy detector layer of IBIS instrument, ISGRI, consists of 128x128 pixels of semiconductor detectors based on of 2 mm thick CdTe crystals. Photons with energy above $\sim$100 keV can interact in a full range of depth of the pixel. When the interaction happens deep the detector, it takes longer for the charge carriers to reach the electrodes and the registered pulse is peaking at a later time (the delay is dominated by the transport of the holes). Due to charge trapping in the detector medium and increase of the role of ballistic deficit with increase of the pulse duration, deeper interactions are registered with smaller pulse height. If not corrected this effect leads to dramatic decrease in the energy resolution. One way to make the correction is in the measurement electronics (e.g. [7, 8, 9]). However, in case of ISGRI it is not feasible since properties of the semiconductors are substantially evolving with time due to the interaction with cosmic rays. ISGRI was pioneering in using biparametric approach: measuring both pulse height and rise time for each energy depostion event [10, 11] and relying on software to perform the correction. Different

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implementations of biparametric methods has become more popular recently due the advance in computing technologies (e.g. [12, 13]).

In OSA10 time evolution of effective detector gain and offset (split in two regions in energy) was modelled with a phenomenological law [14]. The biparametric spectra were corrected to make the positions of the background lines at ∼60 keV and 511 keV compatible with those at the beginning at the mission. This correction did not take into account evolution of energy resolution. It was not possible to predict the change in the detection efficiency of the instrument and the normalization of the spectral response was adjusted to make the spectrum of the Crab compatible with the measurement of INTEGRAL spectrometer SPI.

We developed a time-dependent physical model for the charge loss in the detector. The charge loss due to finite carrier mobility, ballistic deficit and the resolution of the measuring electronics was adjusted using the ground calibration data and in-flight line properties. In the case of in-flight data, we used W fluorescence lines (57.98 keV and 59.31 keV) and a line at 511 keV (originally from the Na^{22} calibration source, later primarily from cosmic ray activation). The model predicts the dependency of the line position on the rise time along the mission with sufficient accuracy. The two-dimentional model line profiles were fitted to the biparametric data for each INTEGRAL revolution.

Total model response describes the distribution of final measured photon energies for each energy of the incident photon. It can be separated in two essential components: non-evolving and evolving.

The first one relates incident photon energy and energy deposited in the detector at given depth in the detector. This response depends on the details of structure of the detector and the whole satellite. The response is modelled by the means of Monte-Carlo simulation of particle propagation with GEANT3 IBIS mass model. This is expected not to vary in time.

The second component of the response is given by the model of the charge loss and electronics resolution. Biparametric resolution of the electronics translates into the energy resolution. Discarding the rise time data channel dimension causes additional increase of the non-diagonal components of the response. In the range of rise times used in the scientific analysis (channels 16-116) the broadening is limited to the elements close to the diagonal of the matrix by choosing a deterministic two-dimensional transformation, a so-called 2D LUT2. This is a change comparing to the 3D LUT2 used before. OSA10 used 3D LUT2 randomly redistributing photon energies according to the distribution expected in a given detector channel from a combination of the charge loss model with a given source model. It can be shown, that this method should be able to reconstruct exactly the source spectrum, if it is identical to the one assumed in the LUT2 generation (typically, powerlaw with a slope of $\Gamma = -2$). The difficulty with this method arises when the spectrum is far from the one assumed. Another difficulty is of technical nature: the 3D LUT2 must be stored in a large file and its generation requires substantial computing time. This becomes a problem when we want to generate a time dependent LUT2. Instead, while using the 2D LUT2, we estimated the bias on the energy reconstruction and the effect of rise time thresholds, and introduced it in the model response. The origin of the bias is in the assumption of the source model in the LUT2. The source model is used in the choice of the energy for pulse height-rise time pair. The choice can be different: for example, the most likely energy, resulting in a given measurement, or average energy. In both cases it depends on the assumed model. We chose to use average energy in the channel, assuming a powerlaw spectrum with the slope of -2. The difference between true incident energy and reconstructed energy estimate is comparable to the resolution. Another essential element of the generation of this response is the loss of a part of the flux beyond the rise time thresholds, slowly evolving due to evolution of the model while the threshsold is set constant.

A non-trivial to model convertion of the charge to the pulse height channel in the whole energy range with sufficient accuracy. OSA10 applied a double conversion law: zero-order below 50 keV and 1-order above. We attempted to avoid sharp transition in this conversion law. Using only the 1-order law and by studying the resulting Crab spectra near the low-energy threshold we noticed that they are becoming progressively more compressed with time. This may be explained by non-linearity of the conversion at very low pulse heights: the spectrum is drifting into lower pulse heights with time and becomes more affected. We modelled this non-linearity by introducing a logarithmic term with energy, contributing only at low energy. This term is small at low energies (up to $\sim 1\%$) at 20 keV and by smoothness intrudes only very small change to the line major positions (at 60 keV 0.2% at the latest time). It does, however, make a substantial difference for the flux evolution at low energy ($25-40$ keV). It is especially difficult to calibrate ISGRI spectral response in this region from the position of the lines, as it is done in the rest of the energy range. The instrumental flurescence lines at $\sim$20 keV have complicated shape, and are subtantially affected by the low threshold at later time, making it impossible to use them for the determination of the evolution of the gain throughout the whole mission. On the other hand this is also the region where the Crab flux as well as, even more importantly, the gradient of the counts spectrum, are both very large, demanding high energy calibration accuracy.

3. Effect on the source spectra

The primary effect on the source spectra consists in reducing complicated non-physical structures previously appearing especially in the range from 80 keV to 100 keV. Figure 1(a) shows different spectra of very bright flare of 1A 0535+26 observed by INTEGRAL IBIS/ISGRI in spacecraft revolution 0839. The OSA10 energy calibration produces a spectrum inconsistent with the SPI measurement. The new calibration is much better compatible. However, in the spectra obtained with of the new calibration we generally observed lower number of counts at high energy (above $\sim$100 keV) then OSA 10. Since the total number of counts is not changed, we also see an increase the flux at lower energy. This can be well seen in the spectrum of the Crab in revolution 0839, Figure 1(b).

4. Crab

Simultaneous fit of all Crab spectrum above 100 keV is close to a powerlaw with a slope of 2.21 ± 0.005 (1 sigma error), $\chi^2_{red}=4.43$, 1116 degrees of freedom. This is in acceptable agreement with the result of INTEGRAL/SPI [15]. The remaining deviation can be explained by progressive softening of the spectrum above 100 keV.

Below 100 keV the prediction of the current model is systematically above the observed spectrum. The effect can be explained by the limitation of the approach used so far for modelling the

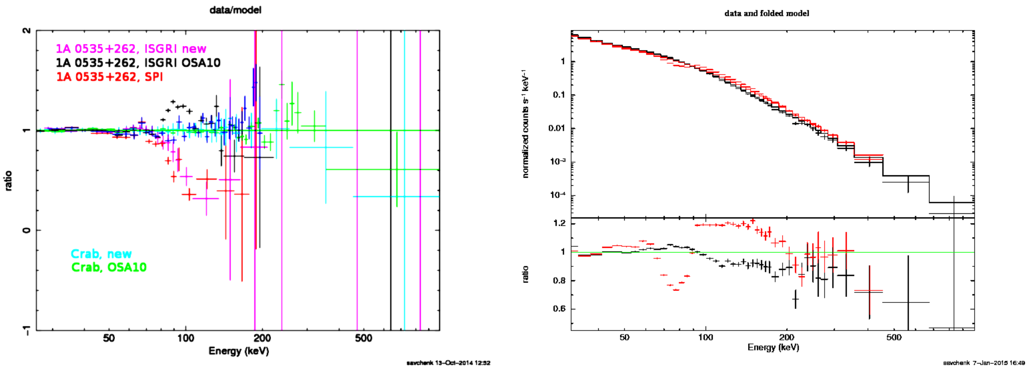

Figure 1: Left: Ratio of the measured spectra of 1A 0535+26 to the model fitted only below 60 keV, not taking into account the cyclotron line. Spectra measured with SPI, and ISGRI (OSA10 and new). Crab spectra with OSA10 and new energy calibration shown for comparison. **Right**: Crab spectra fitted with a broken powerlaw model using modelled response. High energy slope fixed to -2.23, other parameters fitted. Red: OSA10 spectrum assuming a simple simulated response. Black: new spectrum with simulated response.

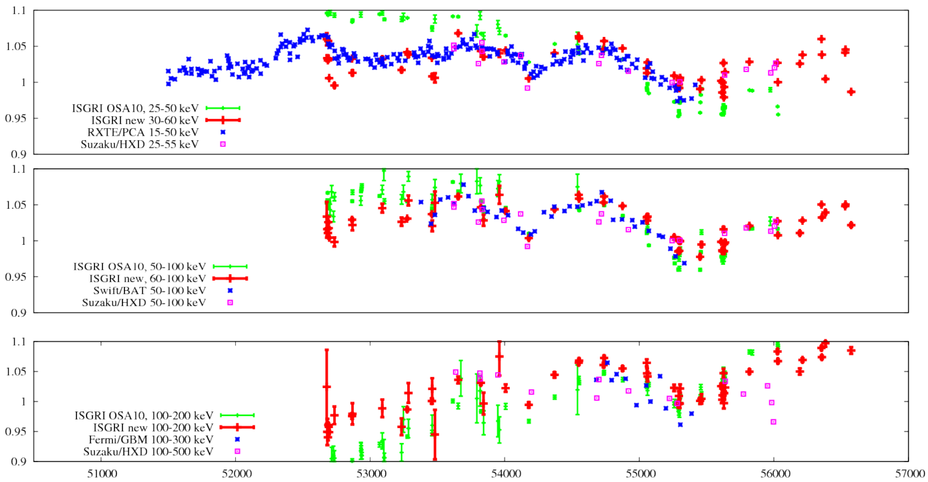

Figure 2: Normalized ISGRI lightcurves of the Crab in 3 energy bands. OSA10 ISGRI from [14], other instruments from [4], [5].

response just below the peak of the effective area and above the absorption edges. This will be addressed in the near future.

The behaviour of the flux lightcurves (Figure 4) in all energy bands is closer to that seen by other instruments, especially at earlier time. The overall evolution of the flux is within 10% for every energy band. However, an overall hardening of the spectrum with time is visible. Whether this is another instrumental effect or a physical property will be more clear after solving the difficulties with the interpretation of the spectral shape below 100 keV.

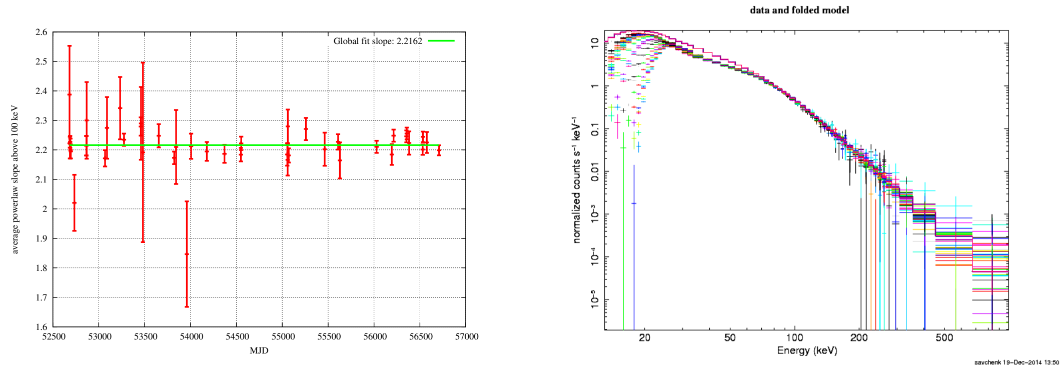

Figure 3: Left: Evolution of the slope of the Crab spectrum above 100 keV. The best fit slope for the overall mission is shown by the horizontal line. The large error bars result from the relatively short observations. **Right:** 46 per-revolution Crab spectra, not corrected for the effect of the low threshold. The evolution of the low threshold can easily be seen. The model lines is a single powerlaw fit only above 100 keV, extrapolated to the lower energies.

5. Discussion and conclusions

We developed an update to the ISGRI energy calibration, for the first time modelling in-orbit evolution of the physical response of instrument. The primary effect of the improvement of the measured shape of the source spectra enables us to measure spectra with a non-trivial shape, for example with an absorption line such as in the case of 1A 0535+26. The average spectrum of the Crab above 100 keV is now consistent with the results of other instruments in the hard X-ray domain. Further effort is required to bring together the prediction of the instrument model and the observed spectra below 100 keV.

Since at high energy the agreement seems to be sufficient, we can exploit it, with caution, to learn about the spectral evolution of the Crab nebula and potentially of other bright sources. Our measurement (Figure 3(a)) shows no spectral evolution: the high energy slopes of all individual revolution spectra are within 2σ of the average slope. It is a matter of further study to check compatibility of our results with the measurement of Suzaku/HXD, who reported detectable evolution of the Crab nebula spectrum [5].

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