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INTEGRAL hard X-ray spectra of the cosmic X-ray background and the Galactic ridge

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We derive the spectra of the cosmic X-ray background (CXB) and of the Galactic ridge X-ray emission (GRXE) in the ∼20–200 keV range from the data of the IBIS instrument aboard the *INTEGRAL* satellite obtained during the four dedicated Earth-occultation observations in early 2006. We analyze the modulation of the IBIS/ISGRI detector counts induced by the passage of the Earth through the field of view of the instrument. Unlike previous studies, we do not fix the spectral shape of the various contributions, but model instead their spatial distribution and derive the expected modulation of the detector counts, which we then fit to the data.
The obtained CXB spectrum is consistent with the historic *HEAO-1* results and falls slightly below the spectrum derived with *Swift*/BAT. A 10 % higher normalization of the CXB cannot be completely excluded, but it would imply an unrealistically high albedo of the Earth. The derived spectrum of the GRXE confirms the presence of a minimum around 80 keV with improved statistics and yields an estimate of ∼0.6 $M_\odot$ for the average mass of white dwarfs in the Galaxy. The analysis also provides updated normalizations for the spectra of the Earth's albedo and the cosmic-ray induced atmospheric emission.
This study demonstrates the potential of *INTEGRAL* Earth-occultation observations to derive the hard X-ray spectra of three fundamental components: the CXB, the GRXE and the Earth emission. Further observations would be extremely valuable to confirm our results with improved statistics.

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1. Introduction

In order to study the X-ray background, a series of four dedicated *INTEGRAL* observations were performed in January and February 2006. The Earth was allowed to pass through the field of view of the instruments shortly after radiation-belt exit while the spacecraft was aimed to point towards a fixed position in the sky. A detailed analysis of these observations has been published previously [2].

We made a complementary analysis focusing on the data of the IBIS/ISGRI instrument. Instead of fixing the spectral shapes of the CXB and the Earth emission components, we attempt to derive the complete spectral information from the observed detector lightcurves in different energy bins. This requires a deep understanding of the instrumental effects and a careful modeling of the spatial distribution of the various contributions from the Galaxy, the Earth and point sources [1].

Preliminary results of this analysis were presented at the *Extreme sky 2009* conference in Otranto, Italy. As the final results are now being published [1], we refer the reader to this publication for a thorough description of the method we used. In these proceedings, we focus on the main results we obtain for the cosmic X-ray background (CXB) in Sect. 2, the galactic ridge X-ray emission (GRXE) in Sect. 3, and the Earth emission in Sect. 4. We end with a short conclusion in Sect. 5.

2. Results on the cosmic X-ray background radiation

We compare the CXB spectrum obtained by our analysis of the IBIS/ISGRI detector lightcurves with the previous *INTEGRAL* results in Fig. 1 *left*. Our approach could significantly increase the useful energy range of the IBIS/ISGRI data towards higher energies. The new results fall slightly below the previous IBIS/ISGRI spectrum, while we get a good agreement with the SPI results [2], except possibly for the first energy bin. The slightly lower emission we obtain now with IBIS/ISGRI is consistent with the *HEAO-1* measurements and its analytical approximation [6]. The flux scaling of the *HEAO-1* spectrum by $+10\,\%$ suggested by [2] is actually not required anymore in the IBIS/ISGRI energy range. The discrepancy appears only below 20 keV for the *INTEGRAL*/JEM-X data that indicate a higher CXB intensity than the *HEAO-1* measurements.

We propose that only the lower-energy data of the *HEAO-1*/A-2 instrument could be scaled up by $\sim 10\,\%$ in intensity, without changing the normalization of the A-4 experiment data [1]. This would be acceptable within the uncertainties and would better match the JEM-X measurements and other results by recent X-ray instruments, which all suggest a higher intensity below 20 keV than obtained by *HEAO-1*/A-2 [7, Fig. 15]. The net effect would be a broadening of the CXB hump and a slight shift of its maximum towards lower energies. The expected qualitative consequence for an AGN population synthesis of the CXB would be a reduction of the contribution of the most highly obscured AGN, in particular the Compton-thick ones [8].

In Fig. 1 *right*, we compare our results to the recent *Swift* [3, 4] and *BeppoSAX* [5] measurements. Our data are consistent with the *Swift*/BAT results and the combined *Swift* spectral model, although they tend to be at a significantly lower intensity. Our data agree very well with the *BeppoSAX*/PDS data provided that they are scaled by a factor of 1.13 in intensity to account for the difference in the Crab normalization with respect to *INTEGRAL* [1].

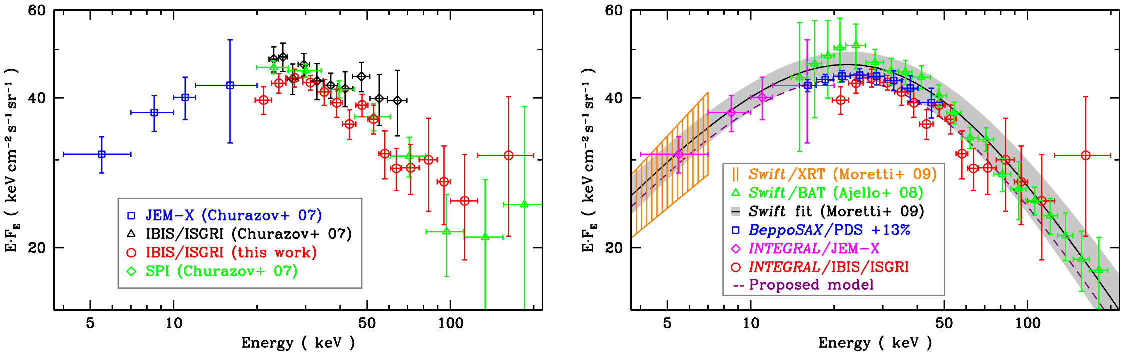

Figure 1: *Left panel:* Comparison of the obtained IBIS/ISGRI CXB spectrum (red circles) with the previous *INTEGRAL* results of IBIS/ISGRI (black diamonds), JEM-X (blue squares) and SPI (green triangles) [2]. *Right panel:* Comparison of the same *INTEGRAL* JEM-X and IBIS/ISGRI spectra with other recent CXB measurements: *Swift*/XRT [4] (orange shaded area) and *Swift*/BAT [3] (green triangles) data with the combined *Swift* model [4] (black line and grey uncertainty area), and the *BeppoSAX* spectrum [5] (blue squares, scaled by +13 %). The analytical model we propose in Eq. (2.1) is shown as a purple dashed line.

Based on the considerations above, we can tentatively suggest a slight adaptation of the analytical description of the CXB proposed by [4, Eq. (4)], as:

$$E^2\,\frac{dN_\gamma}{dE} = E^2\,\frac{0.109\ \mathrm{ph\ cm^{-2}\,s^{-1}\,keV^{-1}\,sr^{-1}}}{(E/28\,\mathrm{keV})^{1.40} + (E/28\,\mathrm{keV})^{2.88}}\,, \tag{2.1}$$

where the only difference – but a correction of a typo in the units – is a change of the break energy from 29 keV to 28 keV. The corresponding spectral shape is at the lower limit of the uncertainty area of the *Swift* model as shown in Fig. 1 *right*.

3. Results on the Galactic ridge X-ray emission

In Fig. 2 *left*, we compare the spectrum of the GRXE we derived from the Earth occultation with previous determinations all rescaled to the central radian of the Milky Way defined in Galactic longitude l and latitude b by $|l| < 30^{\rm o}$ and $|b| < 15^{\rm o}$. We obtain a good agreement between the results of the various instruments, which is quite remarkable for data that were not arbitrarily renormalized, but were rescaled based on a very simple double-Lorentzian model of the GRXE. All three independent *INTEGRAL* measurements reveal a minimum at about 80 keV, but our IBIS/ISGRI results suggest that the minimum is shallower than previously found. The diffuse GRXE below 80 keV is thought to be due to a population of accreting white dwarfs too faint to be resolved into discrete sources in the hard X-rays [9, 10].

The best-fit bremsstrahlung temperature of $kT = 14.7 \pm 1.4$ that we derive for the accretion column onto the pole of the white dwarfs agrees well with the measurements of individual intermediate polar systems detected by *Swift*/BAT [13]. Based on Table 2 in the latter publication, we note that this temperature would correspond to a typical white dwarf mass of $M_{\rm wd} \simeq 0.60 \pm 0.05\,\mathrm{M}_\odot$ according to the model of [14].

Above 80 keV the GRXE spectrum is likely dominated by inverse-Compton emission from the interstellar medium [12]. We derived an intensity at the level of the 2-σ upper limits of [10],

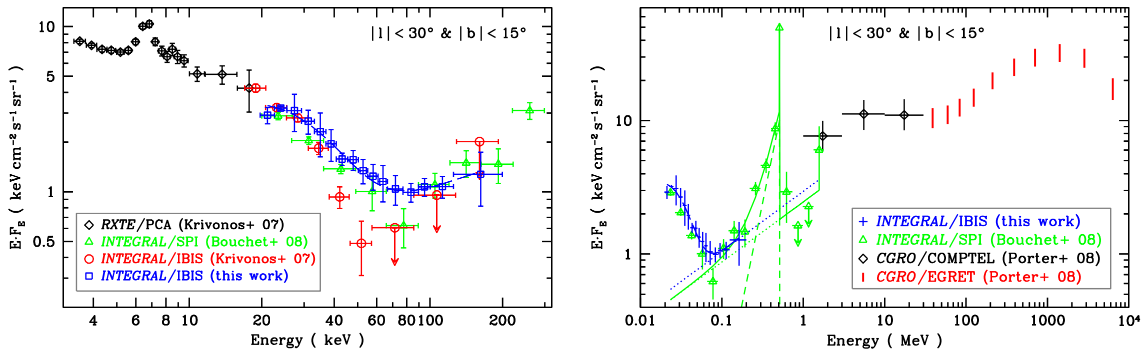

Figure 2: *Left panel:* Comparison of the obtained GRXE spectrum (blue squares and long-dashed line) with recent other determinations: previous *INTEGRAL*/IBIS (red circles) and *RXTE*/PCA (black diamonds) measurements [10], and the *INTEGRAL*/SPI spectrum [11] (green triangles). All data are renormalized to the central radian of the Milky Way defined by $|l| < 30^{\circ}$ and $|b| < 15^{\circ}$. *Right panel:* Comparison of the same *INTEGRAL* IBIS/ISGRI (blue) and SPI (green) spectra, but extended to higher energies with the inclusion of *CGRO*/COMPTEL (black diamonds) and *CGRO*/EGRET (red error bars) measurements from [12, Fig. 3]. The model fit to the SPI data above 100 keV (solid line) consists of a powerlaw continuum (green dotted line), the positronium continuum (short-dashed line) and a narrow electron-positron annihilation line at 511 keV.

in excellent agreement with the latest SPI observations [11] and its derived high-energy powerlaw photon index of $\Gamma = 1.55$. The extrapolation of this power-law is roughly consistent with higher-energy data by the Compton gamma-ray observatory (*CGRO*), as shown in Fig. 2 *right*.

4. Results on the Earth emission spectrum

The Earth emission is found to be very consistent with the spectra obtained previously, as shown in Fig. 3 *left*, although there is a big scatter among the various determinations. This is at least partially due to the modulation of the Earth emission by the solar cycle and a dependence of the observed flux on the spacecraft altitude and the geomagnetic latitude [17]. For instance, the difference in normalization by about a factor of two between the *Swift*/BAT spectrum and our determination can be related to *INTEGRAL* drifting towards an almost polar orbit, while *Swift* has a more equatorial orbit.

A discrepancy we cannot ascribe to a different observation epoch or a different viewpoint is the inconsistency of our results with the spectrum derived from the same *INTEGRAL* observations [2]. We derive a higher Earth emission at low energies and a lower intensity at high energies. This has to be related to the different approach used here with a more detailed modeling of several instrumental effects and the contribution of the point sources.

To better characterize the difference between the two determinations of the Earth spectrum, we show in Fig. 3 *right* the decomposition of the overall Earth emission in the two distinct components considered in both studies. Those are the reflection of the CXB by the Earth – the albedo – and the emission induced by cosmic-ray (CR) interactions in the atmosphere. The spectra of both components can be described by analytical functions fitted to the results of Monte-Carlo simulations for the albedo [16], and the atmospheric emission [17]. In order to fit the overall spectrum of the Earth with these two components, we need to increase the albedo component by $\sim 40\,\%$ and

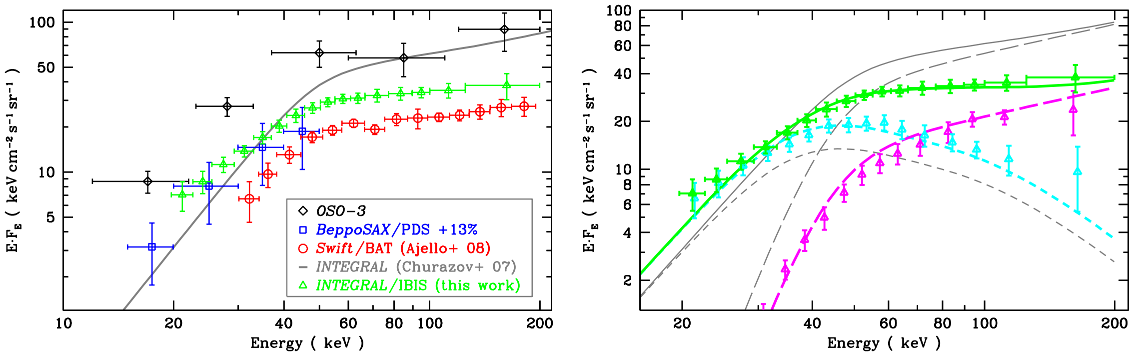

Figure 3: *Left panel:* Comparison of the obtained Earth emission spectrum (green triangles) with previous determinations by various missions. The thin grey line is the previous *INTEGRAL* spectrum [2]. The new IBIS/ISGRI spectrum lies well between the *OSO-3* [15] (black diamonds) and the *Swift*/BAT [3] (red circles) measurements. The values of the *BeppoSAX*/PDS measurements [5] were increased by 13 % (blue squares) as in Fig. 1. *Right panel:* Resulting spectrum of the total Earth emission (green triangles, solid line) with separated contributions from the Earth reflection of the CXB (cyan triangles, short-dashed line) and the CR-induced atmospheric emission (magenta triangles, long-dashed line). The thin grey curves are normalized as derived by [2], whereas the thick colored lines are normalized to match our measurements.

decrease the atmospheric emission by $\sim 60\,\%$ compared to the normalizations suggested by [2]. These important differences are not well understood yet [1].

5. Conclusion

Our analysis of the four *INTEGRAL* Earth observations results in a coherent set of spectra for the CXB, the GRXE and the Earth emission. However, the study was complicated by inherent degeneracy issues that forced us to fit the data with an additional spectral smoothness constraint and adequate input parameters [1].

The obtained IBIS/ISGRI results for the CXB are consistent with the historic *HEAO-1* spectrum, without any scaling in intensity. The obtained spectrum also agrees well with recent *Swift* and *BeppoSAX* determinations. We propose a slight adaptation of the CXB analytical model that would imply a reduced fraction of strongly absorbed AGN than thought in the early 2000s.

The derived spectrum of the Earth emission is very well described by the contribution of two distinct components: the reflection of the CXB that is dominant at lower energies, and the CR-induced atmospheric emission, but with very different normalizations than obtained before [2].

With a total observation time of only about a day, these special types of *INTEGRAL* observations yield a spectrum of the GRXE with comparable statistics as obtained by combining all available *INTEGRAL*/SPI observations. This allows us to observationally estimate the average mass of white dwarfs in the Galaxy. Conducting similar observations in different regions of the Galactic plane would be useful to characterize the longitudinal distribution of the GRXE.

However, it would be even more important to conduct Earth observations away from the Galactic plane to lift any degeneracy related to the presence of the GRXE and point sources. This would lead to a determination of the CXB with improved statistics and less systematics and thus fully exploit INTEGRAL's unique capability to observe the entire Earth from a high-altitude orbit.

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