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INTEGRAL observations of the field of the BL Lacertae object S5 0716+714*

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Abstract. We have performed observations of the blazar S5 0716+714 with *INTEGRAL* on 2-6 April 2004. In the first months of 2004, the source had increased steadily in optical brightness and had undergone two outbursts. During the latter outburst, that occurred in March, it reached the extreme level of $R = 12.1$ mag, which triggered our *INTEGRAL* program. The target has been detected with IBIS/ISGRI up to 60 keV, with a flux of $\sim 3 \times 10^{-11}$ erg s^{-1} cm^{-2} in the 30–60 keV interval, a factor of ~2 higher than observed by the *BeppoSAX* PDS in October 2000. In the field of S5 0716+714 we have also detected the Flat Spectrum Radio Quasar S5 0836+710 and the two Seyfert galaxies Mkn 3 and Mkn 6. Their IBIS/ISGRI spectra are rather flat, albeit consistent with those measured by *BeppoSAX*. In the spectrum of Mkn 3 we find some evidence of a break between ~60 and ~100 keV, reminiscent of the high energy cut-offs observed in other Seyfert galaxies. This is the first report of *INTEGRAL* spectra of weak Active Galactic Nuclei.

Key words. galaxies: active – gamma-rays: observations

1. Introduction

The high energy emission of Active Galactic Nuclei (AGN) carries the most direct and constraining information on the radiation mechanisms and the nature of the central engine. Blazar type AGNs, traditionally subdivided in Flat Spectrum Radio Quasars (FSRQ) and BL Lacertae Objects

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(Urry & Padovani 1995), are very powerful and variable multi-wavelength emitters.

At gamma-ray wavelengths, their spectral output has often a maximum and their variability exhibits the largest amplitudes (Ulrich et al. 1997), making them suitable targets for the *INTEGRAL* mission, particularly during active states. The radio-quiet and less luminous Seyferts exhibit hard X-ray spectra often extending to the soft gamma-ray domain. At these energies spectral cut-offs have been detected in many of these objects by soft gamma-ray experiments like the *CGRO* OSSE and the *BeppoSAX* PDS. Studying these spectral features is relevant to the identification of the emission mechanism responsible for the production of the spectrum at those energies (e.g., Svensson 1996; Haardt et al. 1997; Petrucci et al. 2000).

The BL Lac object S5 0716+714 has been monitored at radio and optical wavelengths by more than 40 telescopes in the northern hemisphere during a Whole Earth Blazar Telescope (Villata et al. 2004) campaign lasting from September 2003 to June 2004. The source had been already observed by *INTEGRAL* in October 2003 during an optically active state (Wagner et al. 2004, in prep.). In January and March 2004, S5 0716+714 was in outburst and achieved its optical historical maximum. In late March 2004 it brightened by 2 magnitudes with respect to its November 2003 level, and by 1 magnitude in ~2 weeks, reaching a magnitude of 12.1 in the optical *R*-band (Sillanpää et al. 2004, in prep.).

The large optical variation observed in March 2004 matched the trigger criteria for our *INTEGRAL* Target-of-Opportunity program for blazars in outburst (Proposal ID: 220049), thus we activated the campaign. Observations with *RXTE* and *XMM-Newton* as well as with ground-based optical and radio telescopes have been carried out simultaneously with *INTEGRAL*. The results of this multiwavelength monitoring will be reported in forthcoming papers. We report here on the *INTEGRAL* observations of the field of S5 0716+714, in which we have also detected another blazar and two Seyfert galaxies.

2. Observations, data analysis and results

INTEGRAL (Winkler et al. 2003) observed S5 0716+714 (Galactic coordinates: $l = 144°$, $b = +28°$) starting from 2004 April 2$^{\rm nd}$, 20:49:25, and ending on 2004 April 7$^{\rm th}$, 00:14:08 UT. In order to optimize the performance of the SPI spectrometer (Vedrenne et al. 2003) we adopted an observing scheme consisting of one pointing of about 2 ks, followed by a slew of 120 s, then by another pointing, and so on, so as to build a rectangular pattern (dither pattern 5×5).

The total duration of the observation was of 280 ks, but the effective exposures of the IBIS/ISGRI (Ubertini et al. 2003; Lebrun et al. 2003), IBIS/PICsIT (Ubertini et al. 2003; Di Cocco et al. 2003), SPI (Vedrenne et al. 2003) and JEM-X (Lund et al. 2003) detectors were of 256, 237, 218, and 189 ks, respectively (only JEM-X1 was used, while JEM-X2 was switched off). This reduction is due to telemetry gaps and dead time corrections (generally affecting all *INTEGRAL* observations), to the occurrence of a failure of the VETO module n. 15, that caused IBIS to be idle for 9 ks, and to the removal of 3 pointings with 13 ks from the SPI data set because of problems in fitting them.

The screening, reduction, and analysis of the *INTEGRAL* data have been performed using the *INTEGRAL* Offline Scientific Analysis (OSA) V. 4.0, publicly available through the *INTEGRAL* Science Data Center[1] (ISDC, Courvoisier et al. 2003a). The algorithms implemented in the software are described in Goldwurm et al. (2003) for IBIS, Westergaard et al. (2003) for JEM-X, and Diehl et al. (2003) for SPI, and we refer the reader to these papers for more details on the data processing and deconvolution of coded–mask telescopes on board *INTEGRAL*.

Only the observations with the IBIS/ISGRI instrument yielded significant source detections, as reported in Sects. 2.1 and 2.2. The IBIS/PICsIT, SPI and JEM-X data were also accumulated into final images. However, no sources are detected in those data.

The upper limit for IBIS/PICsIT is 7.3×10^{-10} erg s^{-1} cm^{-2} in the 252–336 keV range (292 mCrab). In the most sensitive SPI energy range, 20–40 keV, the spectrometer achieved a marginally significant detection for Mkn 3: $8.3 \pm 3.5 \times 10^{-4}$ ph s^{-1} cm^{-2} (4.6 mCrab). For S5 0716+714, S5 0836+710, and Mkn 6 the 3σ upper limit is $\sim 10^{-3}$ ph s^{-1} cm^{-2} (6 mCrab). The extrapolation of the ISGRI spectra of S5 0836+710, Mkn 3 and Mkn 6 (see Sects. 2.1 and 2.2) to lower energies falls by a factor from 2 to 20 below the sensitivity of the JEM-X image. The JEM-X 3σ upper limits for S5 0716+714, S5 0836+710, Mkn 3 and Mkn 6 are 6, 10, 8, 6 mCrab (5–20 keV), respectively.

No data were acquired with the Optical Monitor (Mas-Hesse et al. 2003).

2.1. IBIS observation of S5 0716+714

A first inspection of the IBIS/ISGRI data revealed the presence of high background, with some structures. However, in the final mosaic of all the available data (i.e., the weighted combination of the individual pointings), no systematic effects have been found.

S5 0716+714 is detected with signal-to-noise ratio 4.5σ in the energy band 30−60 keV, for a count rate of 0.11 ± 0.04 counts s^{-1}. Since the source was better detected in the first part of the *INTEGRAL* observation, indicating that it was declining, we selected and accumulated the individual pointings of the early portion of the monitoring, for which the signal-to-noise ratio at the position of the blazar is larger than 1. This reduces the useful exposure to a total of 84 ks, but allows us to improve the significance of the detection of S5 0716+714 to 6.5σ in the 30−60 keV energy range. No signal is detected above 60 keV.

Given the low signal-to-noise ratio, it was not possible to study the intra-orbit variability of the source, nor to extract a spectrum.

In order to evaluate the flux of the source we assumed a spectrum identical to that of the Crab nebula ($\Gamma = 2.1$) and scaled the normalization via the count rates ratio in the

[1] http://isdc.unige.ch/index.cgi?Soft+download

30–60 keV range (Table 1). Note that our flux measurement is only representative of the higher state of the source during the observation, and not of the overall average state.

2.2. Other AGNs in the IBIS field of view

The large field of view of IBIS (19° × 19° at half response) allowed us to observe serendipitously other sources. Specifically, three additional AGNs are detected in the IBIS/ISGRI image with higher significance than our blazar target (Table 1), and up to 100 keV. Also for these sources, the detections in the individual pointings are not significant, and therefore it is not possible to study their intra-orbit variability. However, the signal-to-noise ratio of the summed image is sufficiently high to allow the extraction of an average spectrum.

Since spectral reconstruction is very sensitive to the background correction in weak sources, we have extracted the spectra following two independent procedures, as recommended in the OSA guidelines[2]. For each source, we have obtained both a coadded spectrum from the spectra extracted from individual pointings, and a spectrum constructed from the imaging in the same energy bands used for spectral extraction. These are found to be consistent with each other in all sources. We have used the spectra obtained with the former method for spectral analysis. In order to apply the χ^2 statistics, the spectral signal has been binned in intervals where the significance is at least 3σ.

In the energy range ≈60–80 keV the IBIS spectra are affected by instrumental features (Terrier et al. 2003), that are not well modeled by the response matrix. The OSA V. 4 software reduces this problem only partially, therefore, considering also the relevance of the background relative to the flux levels of our sources, we conservatively excluded the above spectral region from the analysis.

We fitted single power-laws to the spectra of S5 0836+710 (Fig. 1) and Mkn 6 (Fig. 2) using the `xspec` package (v. 11.3.1). No systematic errors have been added in the fitting; we estimate the flux calibration uncertainties to be of the order of ∼10%.

In Mkn 3, the spectral point at ∼100 keV (see Fig. 3) makes a single power-law fit inadequate (the χ^2 is 13 for 4 degrees of freedom); therefore we used a broken power-law, although the high energy index Γ_2 is obviously poorly constrained by the isolated point at 100 keV (see contour plot in Fig. 4).

We have also tried a fit with a power-law plus an exponential cutoff. If the power-law photon index is left as a free parameter, it assumes an unreasonably flat value, $\Gamma \simeq -0.07$, inconsistent with the power-law index which best fits the spectral points at energies lower than 100 keV, $\Gamma = 1.3$. A contour plot of the fitted photon index vs. high energy cut-off is shown in Fig. 5. By freezing instead the photon index to $\Gamma = 1.3$, we obtain a cut-off energy of ∼87 keV with an unacceptably high χ^2 of 8.6 for 4 degrees of freedom. By adding in quadrature to the statistical uncertainties a systematic error as large as 25% we recover a $\chi^2 = 4$ for 4 degrees of freedom and the cut-off energy is $E = 95^{+105}_{-40}$ keV.

[2] `http://isdc.unige.ch/Soft/download/osa/osa_sw/osa_sw-4.0/osa_issues-4.0.txt`

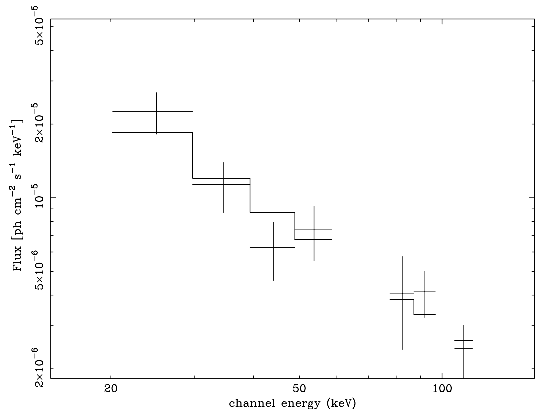

Fig. 1. IBIS/ISGRI spectrum of S5 0836+710. The overplotted step-like curve is the best fit single power-law.

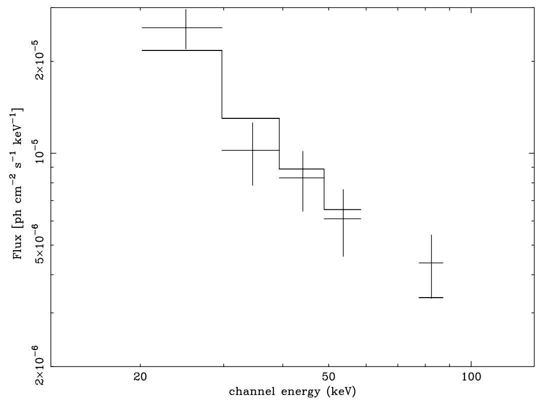

Fig. 2. IBIS/ISGRI spectrum of Mkn 6. The overplotted step-like curve is the best fit single power-law.

Therefore, we formally prefer the broken power-law rather than the cut-off power-law model. At best, the latter suggests a cut-off energy larger than ∼50 keV. We stress that the choice of the best interpretation of the spectral shape of Mkn 3 largely relies upon the point at ∼100 keV, that is very sensitive to background subtraction. A more robust spectral modeling must await a more accurate spectral measurement at these energies.

The results of the spectral analysis are reported in Table 1. The spectra, along with their best-fit models, are reported in Figs. 1–3.

3. Discussion

We observed the blazar S5 0716+714 with *INTEGRAL* while it was undergoing a major optical outburst and detected the source in a somewhat higher (about a factor of 2) gamma-ray state than observed in October 2000 (Tagliaferri et al. 2003). At that epoch the optical flux was slightly lower ($R \simeq 12.5$) than that observed in March 2004 at maximum brightness. The *BeppoSAX* PDS spectrum suggests that the soft gamma-rays are due to inverse Compton scattering of relativistic particles (Tagliaferri et al. 2003; Giommi et al. 1999; see also the last column of Table 1, where the indices of the PDS spectra of our sources are reported for comparison with the present results).

Table 1. Sources detected in the IBIS/ISGRI field of S5 0716+714.

Object	AGN type	z	CR[a]	Flux[b]	Range[c]	Γ_1^d	Γ_2^d	E_b^e	χ^2	d.o.f.	$\Gamma_{\rm PDS}^f$
S5 0716+714	BL Lac	...	0.36 ± 0.07^g	3.1	30–60	...	...	...	...	...	$1.6 \div 2.0$
S5 0836+710	FSRQ	2.172	0.54 ± 0.05	4.6	20–100	1.3 ± 0.3^h	...	...	4.1	5	1.31 ± 0.03
Mkn 6	Sy 1.5	0.019	0.49 ± 0.06	4.6	20–100	$1.5^{+0.5}_{-0.4}$	...	...	3.7	3	1.8 ± 0.2
Mkn 3	Sy 2	0.013	0.82 ± 0.05	7.4	20–100	1.3^i	> 2.5	80 ± 20^h	2.5	3	1.8 ± 0.1

[a] IBIS/ISGRI count rate in the detection energy range (Col. 6), in counts s^{-1}.
[b] Fitted flux in the detection energy range (Col. 6), in 10^{-11} erg s^{-1} cm^{-2}. Calibration uncertainties are $\sim$10%.
[c] Energy interval to which count rates (Col. 4) and fluxes (Col. 5) are referred, in keV.
[d] Photon index: $f_E \propto E^{-\Gamma}$.
[e] Break energy, in keV.
[f] Photon index measured with the *BeppoSAX* PDS at previous epochs.
[g] Uncertainties on the count rates are 1σ.
[h] Uncertainties on the photon indices and break energy are 1.6σ.
[i] Γ_1 has been frozen to the index of the single power-law which best fits the spectrum below 100 keV, $\Gamma = 1.3 \pm 0.4$.

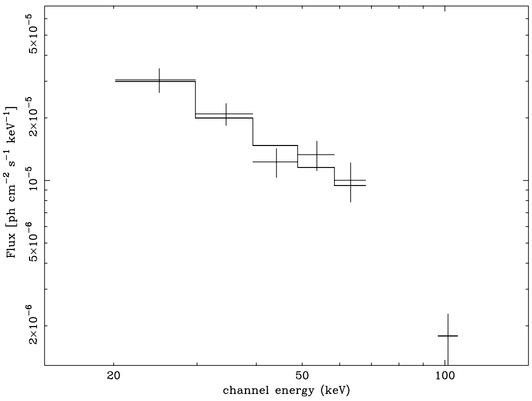

Fig. 3. IBIS/ISGRI spectrum of Mkn 3. The overplotted step-like curve is the single power-law which best fits the spectrum below 100 keV. The point at 100 keV is clearly below this curve.

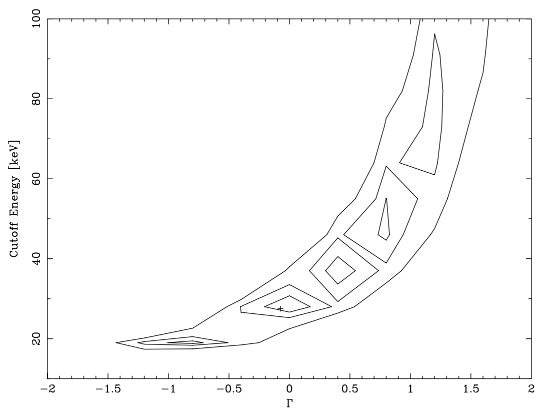

Fig. 5. Contour plot of cut-off energy vs. photon index for the cut-off power-law model fit of Mkn 3 spectrum.

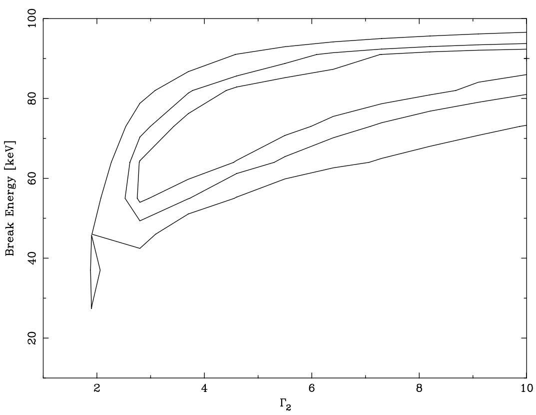

Fig. 4. Contour plot of break energy vs. photon index for the broken power-law model fit of Mkn 3 spectrum.

In the same field of our primary target we also detected the high redshift blazar S5 0836+710, belonging to the FSRQ subclass (Urry & Padovani 1995), and two bright Seyfert galaxies, Mkn 3 and Mkn 6, all with brighter fluxes than S5 0716+714 (Table 1).

The spectral index of S5 0836+710 is consistent with that determined through *CGRO* BATSE (Malizia et al. 2000) and *BeppoSAX* PDS (Tavecchio et al. 2002) observations during higher emission states (our measured flux is a factor of $\sim$3 lower than found by both BATSE and *BeppoSAX*). The flat spectral slope favours the interpretation of the high energy spectrum as Compton scattering of relativistic electrons off external radiation, as opposed to synchrotron-self Compton, in FSRQ (Sikora et al. 1994).

The IBIS/ISGRI spectral slope of the Seyfert Mkn 6 is flatter, although consistent with that measured by the *BeppoSAX* PDS (Malizia et al. 2003a; Immler et al. 2003), within our rather large errors. Similarly, the flux level in the IBIS/ISGRI observation is consistent with that measured by the PDS.

Our IBIS/ISGRI spectrum of Mkn 3 has an index consistent with that determined by OSSE ($\Gamma \simeq 1.3$, Zdziarski et al. 2000) and suggests the presence of a high energy cut-off, at an energy approximately compatible with those of the breaks detected in other Seyfert objects and radiogalaxies by OSSE and *BeppoSAX*, although on the lower energy side with respect to the average break energy determined by *BeppoSAX* for Seyfert 2 galaxies (Johnson et al. 1997; Grandi et al. 1998; Piro et al. 1998; Nicastro et al. 2000; Zdziarski & Grandi 2001; Zdziarski et al. 2000; Gondoin 2001; De Rosa et al. 2002; Malizia et al. 2003b; Deluit & Courvoisier 2003). However, no evidence of a cut-off was found in Mkn 3 by Cappi et al. (1999) at least up to 150 keV, the maximum energy at which the source was detected by the *BeppoSAX* PDS. Therefore, while considering our detection of a cut-off tentative, we cannot exclude a variable cut-off energy. We note in fact that the flux detected by the PDS was ~30% higher than that detected by IBIS, and the spectral slope ($\Gamma \simeq 1.8$) marginally steeper (see Cappi et al. 1999). A similar correlation of cut-off energy and spectral steepness has been observed with *BeppoSAX* in the Seyfert 1 NGC 5548 (Nicastro et al. 2000; Petrucci et al. 2000). A better exposed *INTEGRAL* ISGRI and/or SPI spectrum would be necessary to confirm our finding.

INTEGRAL has so far significantly detected a number of radio-quiet and radio-loud AGNs (Bassani et al. 2004; Beckmann et al. 2004; Bird et al. 2004), among which the brightest known radio-loud AGN, 3C 273 (Courvoisier et al. 2003). Our observation of S5 0716+714 and serendipitous detection of three additional AGNs proves *INTEGRAL* to be effective, even with relatively short exposure observations, in the study of bright extragalactic sources at high Galactic latitudes and underscores the importance of instruments with a large field of view and good angular resolution for the investigation of gamma-ray-loud AGNs. S5 0836+710 is the second highest redshift AGN detected by *INTEGRAL*, after PKS 1830-21 at $z = 2.507$ (Bassani et al. 2004), which indicates that *INTEGRAL* can also play a role in exploring the high redshift universe.

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