THE HIGH-ENERGY EMISSION OF GRO J1655−40 AS REVEALED WITH INTEGRAL SPECTROSCOPY OF THE 2005 OUTBURST

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ABSTRACT

We present broadband (3–500 keV) INTEGRAL X-ray spectra and X-ray/optical light curves of the luminous black hole X-ray transient and relativistic jet source GRO J1655−40. Our analysis covers four Target of Opportunity observations of the outburst that started in 2005 February. We find that the high-energy emission of GRO J1655−40 can be modeled well with an unbroken power law (with photon indices $\Gamma$ of 1.72 ± 0.03 and 2.21 ± 0.04 for the first and second observations). These correspond to hard and thermal-dominant states, respectively. In contrast to many other black hole spectra, high-energy complexity in the form of a break or cutoff is not required for the hard state, contrary to previous expectations. We show for the first time that Comptonization by nonthermal electrons is the dominant process behind the high-energy emission in the hard state. We discuss our results in terms of models for broadband emission and accretion flows in stellar-mass black holes.

Subject headings: accretion, accretion disks — binaries: general — black hole physics — gamma rays: observations — radiation mechanisms: nonthermal — radiation mechanisms: thermal

1. INTRODUCTION

GRO J1655−40 is a black hole X-ray binary whose parameters are well known. Also called Nova Scorpii 1994, the source was discovered with the Burst and Transient Source Experiment on board the Compton Gamma Ray Observatory (CGRO) on 1994 July 27 (Zhang et al. 1994). The optical counterpart was discovered soon after by Bailyn et al. (1995b; $V \sim 14.4$ mag). Subsequent optical studies regarding the properties of the light curve during the outburst and quiescent period showed that the system is a low-mass X-ray binary composed of a blue subgiant (spectral type F4 IV) as the secondary and a black hole as the primary ($m_{\text{BH}} = 7.02 \pm 0.22 M_{\odot}$; Orosz & Bailyn 1997). The system is located at a distance of 3.2 kpc as measured by Tingay et al. (1995). Although Foellmi et al. (2006) have recently suggested a smaller distance, their parameters imply that the donor star would not fill its Roche lobe. Bailyn et al. (1995a) established the orbital inclination of the system as $\sim 70^\circ$ (see also Orosz et al. 1997; van der Hooft et al. 1998); an independent determination made by Kuulkers et al. (1998) based on X-ray flux dips constrained the inclination of the system to be $60^\circ$–$75^\circ$. The inclination of the inner disk may be as high as $85^\circ$, indicating a slight misalignment with the binary system (Hjellming & Rupen 1995).

GRO J1655−40 has displayed some of the most extreme behavior and phenomena yet observed from any black hole X-ray transient. Strohmayer (2001) discovered a pair of high-frequency quasi-periodic oscillations at 300 and 450 Hz in power spectra from the 1996/1997 outburst of the source. If the higher frequency is associated with the Keplerian frequency at the innermost stable circular orbit (ISCO; Shapiro & Teukolsky 1983), located at $R_{\text{ISCO}} = 6R_\text{g}$ for a Schwarzschild black hole or $R_{\text{ISCO}} = 1.25R_\text{g}$ in the case of a maximal Kerr black hole with $a = 0.998$ (where $R_\text{g} = GM/c^2$ is the gravitational radius and $a = cJ/GM^2$; see Bardeen et al. 1972; Thorne 1974), the frequency observed indicates that GRO J1655−40 harbors a spinning black hole. This suggestion is broadly consistent with spin estimates based on fits to skewed Fe K emission lines ($a \geq 0.9$ from $r \leq 1.4R_\text{g}$; Miller et al. 2005). GRO J1655−40 has also exerted extremely relativistic radio jets (Hjellming & Rupen 1995). Finally, unbroken power-law emission (i.e., without a cutoff) from GRO J1655−40 has been detected out to 800 keV (Tomsick et al. 1999), offering a crucial insight into high-energy processes in black hole systems.

High-energy processes and the periods of correlated behavior known as “states” in black hole binaries are the focus of this paper. Three active states are commonly recognized in the soft X-ray domain (see Remillard & McClintock 2006): the nonthermal-dominant or hard state (formerly called low/hard), the thermal-dominant state (formerly called high/soft), and the steep power law state. In addition, there are transitions between these states, which are often referred to as intermediate states. In the hard state, the soft X-ray emission is very weak and the spectrum is dominated by some kind of nonthermal emission that is broadly consistent with a power law at higher energies ($\gtrsim 20$ keV). It has been known for a long time that black hole spectra in the hard state are exponentially cut off at $\sim 100$ keV (see Grove et al. 1998 and references therein). A radio jet is usually inferred in this state from flat radio spectra (see Fender et al. 2004 for a unified model of X-ray states and radio emission in black hole X-ray transients). In the thermal-dominant state, the disk dominates the X-ray emission. Although high-energy emission ($\gtrsim 20$ keV) is also seen in this state, it is weaker and generally steeper and extends up to 800 keV without any break (Grove et al. 1998). In the steep
power law state, these emission components are combined—both the disk and the nonthermal power law are strong, although the power law state, these emission components are combined—both the disk no longer follows the $L \propto T^4$ relation that is observed in the soft state (Kubota et al. 2001; Saito et al. 2007).

Several models have been proposed to explain the physical conditions in the innermost accretion flow and the nature of hard X-ray emission in the various states, but a clear picture has not yet been achieved. At low mass accretion rates, hard X-ray emission may arise in an inner region filled by a hot ($kT \sim 100$ keV), radiatively inefficient, advection-dominated accretion flow (ADAF; Narayan 1996; Esin et al. 2001). A recent study by Yuan & Zdziarski (2004) shows that the ADAF scenario is not able to explain the relatively high luminosities that have been observed in the hard states of some black hole X-ray binaries. Alternatively, some recent models suggest that direct synchrotron emission, synchrotron self-Comptonization in a jet, or both may dominate the hard X-ray emission (Markoff et al. 2001, 2003, 2005). Both at low and at high mass accretion rates, thermal Comptonization in a corona (fed by seed photons from the disk) may also be an important source of hard X-ray emission (see, e.g., Frontera et al. 2003). An alternative source of Comptonization that is less reliant on the disk is bulk motion Comptonization (BMC; Ebisawa et al. 1996; see also Titarchuk & Shrader 2002 for a comoving Comptonizing medium). In this case, the Comptonization is due to bulk motion of an almost free-falling (convergent accretion) flow close to the black hole.

A thermal distribution of the Comptonizing particles (electrons) necessarily leads to a turnover in the emitted spectrum around $kT_e$; therefore, thermal Comptonization should lead to a turnover near the electron temperature of the corona, $kT_e$. Synchrotron emission and a nonthermal electron distribution do not necessarily predict such a turnover, however, and this difference provides an observational tool to distinguish which processes dominate the hard X-ray emission in different black hole states. The high-energy sensitivity of the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) is especially well suited to this purpose.

In this paper, we report on observations of GRO J1655–40 made with INTEGRAL during the outburst that began in February of 2005 (Markwardt & Swank 2005). In § 2, we describe our observations, and in § 3 we show the light curves obtained with the JEM-X, ISGRI, SPI, and OMC instruments on board INTEGRAL and with the Rossi X-Ray Timing Explorer (RXTE) and discuss the possible origin of their evolution. In § 4, we present our spectral analysis made with JEM-X, ISGRI, and SPI. Finally, in § 5 we discuss our results in the context of the different models and theories present in the literature.

2. OBSERVATIONS

2.1. INTEGRAL Observations

The data cover the first part of the 2005 outburst and were obtained with INTEGRAL using the following instruments: the Spectrometer on INTEGRAL (SPI; Vedrenne et al. 2003), the INTEGRAL Soft Gamma-Ray Imager (ISGRI; Lebrun et al. 2003), the Joint European X-Ray Monitor (JEM-X; Lund et al. 2003), and the Optical Monitoring Camera (OMC; Mas-Hesse et al. 2003). ISGRI is optimized for 15 keV to 10 MeV imaging, and SPI is optimized for high-resolution spectroscopy in the 18 keV to 8 MeV band. The former provides an angular resolution of 12' full-width at half-maximum (FWHM) and an energy resolution $E/\Delta E$ of $\approx 12'$ (FWHM) at 100 keV. SPI provides an angular resolution of 2.8' (FWHM) and an $E/\Delta E$ of 430 FWHM at 1.3 MeV. JEM-X has a fully coded field of view (FOV) of 4.8' diameter and an angular resolution of 3' FWHM. JEM-X has medium-resolution spectral capabilities in an energy range of 3–35 keV. The OMC is an optical monitor with an FOV of $5' \times 5'$ and an astrometric resolution of better than 1.0' and performs optical photometry in the $V$ band down to 18th magnitude.

Our program consisted of four Target of Opportunity (ToO) observations of 100 ks each, spread from 2005 February 27 to April 11 (we refer to these as epochs 1–4 below; see Table 1 for more details). The difference in the exposure times between the INTEGRAL instruments given in Table 1 (JEM-X, ISGRI, and SPI) are due to differences in dead time and variations in efficiency along the fields of view. The dithering pattern used during the observations was 5' × 5' (a square of 25 pointings separated by 2.17' centered on the main target of the observation); this is the best pattern in order to minimize background effects for the SPI and ISGRI instruments in crowded fields. Data reduction (in the case of JEM-X, ISGRI, and SPI) was performed using the standard Offline Science Analysis (OSA, ver. 5.1) software package available from the INTEGRAL Science Data Centre (ISDC; Courvoisier et al. 2003). For SPI, because of the lower angular resolution and crowded field of view in gamma rays at this position of the sky [(l, b) = (344.98°, +2.46°); see Fig. 1], we used a nonstandard procedure in the analysis of the data, described by Deluit (2005) and Roques & Jourdain (2005). For the same reason, in the case of the OMC we used a standard pipeline available in OSA version 6.0 (recently delivered) for extraction of fluxes. For the OMC, all the public data available from the ISDC were downloaded (this resulted in only a slight increase in the amount of data). Because of the steep fall in response in the case of JEM-X, and because of its reduced FOV ($\approx 5'$ of diameter), we limited the pointing radius with respect to GRO J1655–40's position to be within 4'. In the case of SPI and ISGRI, with large fully coded fields of view (16' × 16' for SPI and 8.3' × 8' for ISGRI), pointing selections were not necessary. In total, 199 individual pointings (or Science Observations) were delivered on each of the 11 epochs (we refer to these as epochs 1–4 below; see Table 1 for more details). The difference in the exposure times between the INTEGRAL instruments given in Table 1 (JEM-X, ISGRI, and SPI) are due to differences in dead time and variations in efficiency along the fields of view. The dithering pattern used during the observations was 5' × 5' (a square of 25 pointings separated by 2.17' centered on the main target of the observation); this is the best pattern in order to minimize background effects for the SPI and ISGRI instruments in crowded fields. Data reduction (in the case of JEM-X, ISGRI, and SPI) was performed using the standard Offline Science Analysis (OSA, ver. 5.1) software package available from the INTEGRAL Science Data Centre (ISDC; Courvoisier et al. 2003). For SPI, because of the lower angular resolution and crowded field of view in gamma rays at this position of the sky [(l, b) = (344.98°, +2.46°); see Fig. 1], we used a nonstandard procedure in the analysis of the data, described by Deluit (2005) and Roques & Jourdain (2005). For the same reason, in the case of the OMC we used a standard pipeline available in OSA version 6.0 (recently delivered) for extraction of fluxes. For the OMC, all the public data available from the ISDC were downloaded (this resulted in only a slight increase in the amount of data). Because of the steep fall in response in the case of JEM-X, and because of its reduced FOV ($\approx 5'$ of diameter), we limited the pointing radius with respect to GRO J1655–40's position to be within 4'. In the case of SPI and ISGRI, with large fully coded fields of view (16' × 16' for SPI and 8.3' × 8' for ISGRI), pointing selections were not necessary. In total, 199 individual pointings (or Science Windows — each having an exposure time lasting from 1800 to 3600 s and following a 5' × 5' dither pattern on the plane of the sky; Courvoisier et al. 2003) were used for both SPI and ISGRI, 96 pointings for JEM-X, and 66 pointings for OMC.

2.1.1. Extraction of Light Curves

GRO J1655–40 was covered with INTEGRAL as part of the Galactic Bulge Monitoring Program (Kuulkers et al. 2007).
Precisely at the start of this program, GRO J1655−40 was reported to have become active (Markwardt & Swank 2005). The subsequent outburst of GRO J1655−40 was also followed with the RXTE All-Sky Monitor (ASM) and with a dense program of pointed RXTE Proportional Counter Array (PCA) observations (Homan 2005). In Figure 2, we show the ISGRI (20–60 and 60–150 keV), ASM (2–12 keV), and OMC (optical) light curves. The light curve derived from ISGRI in the 20–60 and 60–150 keV energy bands had 1800 s exposures (about 150 counts s\(^{-1}\)) corresponding to 1 crab on-axis in the 20–60 keV energy band; see Appendix A of Kuulkers et al. (2007). GRO J1655−40 was observed at a large off-axis angle (≈15° from the center of the FOV, so in the partially coded FOV of ISGRI and not visible with the X-ray monitor JEM-X).

Since GRO J1655−40 is located in a very crowded field for the OMC, in the flux extraction process we forced the photometric aperture to be centered at the source coordinates, which were taken from the OMC Input Catalogue (Domingo et al. 2003). The typical limiting magnitude of the OMC in the Galactic bulge is between \( V = 15 \) and \( V = 16 \) (3 \( \sigma \)). This value depends strongly on sky background and source contamination. In our case \((l, b) = (344.98°, +2.46°)\), we can confidently reach limiting magnitudes down to \( V = 16 \) (3 \( \sigma \)). For each INTEGRAL pointing, the OMC monitors the sources in its FOV by means of “shots” of variable integration time. Typical values in the range 10–200 s (currently 10, 50, and 200 s) are used to optimize sensitivity and to minimize readout noise and cosmic-ray effects. For the faintest objects, several 200 s exposures in the same pointing can be combined during data analysis on the ground. We obtained one photometric point by combining several 200 s OMC shots. To increase the signal-to-noise ratio, we combined the individual photometric points of every pointing and calculated the final photometric points by taking running averages in order to minimize the dispersion.

**2.1.2. Extraction of Spectra**

For JEM-X and ISGRI, individual spectra were obtained for each pointing. The spectra were then combined to obtain an averaged spectrum per epoch using the spe_pick OSA tool and standard procedures (see Chernyakova 2005; Chernyakova et al. 2005) to rebin the response matrices. In the case of SPI, we directly derived one spectrum per revolution. The SPI spectra were extracted over an energy range of 23–8000 keV (with 26 logarithmic bins) using the SPIROS package within OSA, applying maximum likelihood optimization statistics (Skinner & Connell 2003). Because of the crowdedness of the field and the low spatial resolution of the instrument (sources separated by less than 2.8° cannot be resolved), it was necessary to apply special techniques to extract spectra (see Roques & Jourdain 2005; Deluit 2005). These included accounting for variability of the sources present in the FOV. The background\(^9\) was determined by using flat fields from particular INTEGRAL revolutions (revolution 220 in our case—the publicly available flat field closest in time to our period of observations), and the use of background method 3 (determination of the background based on some specific flat-field INTEGRAL observations). Because SPI is a high-resolution spectrograph in its energy range (20–8000 keV) with a reduced number of detectors (namely, 19), it is not optimized for the detection of sources without taking into account previous information about their spatial distribution. Thus, we used as an input catalog of sources those obtained from ISGRI in the (20–40) keV mosaic images (see Fig. 1).

The signal from GRO J1655−40 was too soft to detect any emission in the last two epochs with SPI. We combined single-revolution SPI spectra from each epoch, since there was no significant evolution and in order to increase the signal-to-noise ratio.

\(^9\) Because JEM-X, ISGRI, and SPI are detectors based on coded-mask optics, the detection of sources is made on the basis of a deconvolution, also taking into account background, in an iterative process called IROS (Iterative Removal of Sources). In OSA 5.1, the spectra obtained are always background subtracted, and it is not necessary to apply any background correction in XSPEC to the obtained spectra. The light curves obtained are also background subtracted. However, in JEM-X analysis it is possible to skip the level of background subtraction. We refer the reader to Roques et al. (2005), Goldwurm et al. (2003), Westergaard et al. (2003), and Dubath et al. (2005) for more details.
This resulted in one SPI spectrum in revolution 290 and another one combining revolutions 295 and 296. The same was done for the low-energy instruments (JEM-X and ISGRI), thus yielding four spectra, namely, one for each epoch, as can be seen in Table 1. We applied 2% systematic errors to the JEM-X, ISGRI, and SPI spectra. We restricted ourselves to the energy ranges $5 \lesssim 30$, $23 \lesssim 600$, and $23 \lesssim 800$ keV for the JEM-X, ISGRI, and SPI spectral analysis, as recommended by Lubinski et al. (2005). The SPI and ISGRI spectra were rebinned at high energies ($\gtrsim 200$ keV) with the FTOOLS grppha procedure to reach a detection level of $3 \sigma$.

3. ANALYSIS OF LIGHT CURVES

Figure 2 shows the GRO J1655–40 light curves obtained with ISGRI (from the INTEGRAL Galactic Bulge Monitoring Program; Kuulkers et al. 2007) in two energy bands ($60–150$ keV and $20–60$ keV), together with that from OMC (optical). The public RXTE ASM ($2–12$ keV) light curve for the same period of time is also shown for comparison.

The light curves in Figure 2 only show the first month of outburst of GRO J1655–40. For a full outburst light curve, see Brocksopp et al. (2006), where the X-ray light curve obtained by Swift is shown jointly with that obtained in the optical and ultraviolet band using the Ultraviolet/Optical Telescope (UVOT) on board Swift. In Figure 3, we show the RXTE PCA light curve in the $2–60$ keV range plus the evolution of the hardness ratio (calculated as the ratio of the $9.4–18.2$ keV and $2.8–5.7$ keV count rates) during the entire outburst, taken from J. Homan et al. (2007, in preparation). The light curves were made from 520 RXTE observations, with one (averaged) data point for each observation. The horizontal lines shown in Figures 2 and 3 indicate the time intervals (100 ks each, in four observations) over which our average spectra were obtained. Note that black hole transients usually begin and end their outbursts in the hard state (see Nowak 1995; Fender et al. 2004; Homan & Belloni 2005), and the 2005 outburst of GRO J1655–40 is no exception. As can be seen in Figure 2, the beginning of the outburst started at high energies ($20–150$ keV) rather than with softer X-rays ($2–10$ keV). Moreover, as can also be seen from the hardness ratios in Figure 3, the observations of epoch 1 correspond to the hard state (see §5). The other three epochs were during a period when the source spectrum was much softer. However, it should be noted that it was only later in the outburst that the softest spectra (corresponding to the thermal-dominant state) were observed (see Fig. 3).

The first indications of an impending outburst of GRO J1655–40 came from RXTE PCA bulge-scan observations on 2005 February 19 (Markwardt & Swank 2005). On February 20, observations made with the PANIC instrument on the Magellan 6.5 m Baade Telescope at Las Campanas Observatory revealed a $J$-band (near-infrared) magnitude of $13.2 \pm 0.1$ (Torres et al. 2005), indicating that GRO J1655–40 was brighter by $\approx 0.5$ mag in $J$ relative to its magnitude in quiescence ($J = 13.7 – 14$; Greene et al. 2001). On the same date, a radio detection of the source was reported (Rupen et al. 2005).
As can be seen from Buxton & Bailyn (2005) and Brocksopp et al. (2006), the optical light curve behaves differently from the X-ray. The optical behavior consists of an increase in flux up to a constant level at MJD 53,455. This behavior can also be seen with the OMC, because the flux in the optical light curve was increasing, reaching a constant and detectable value ($V \sim 15$ mag) at MJD 53,455. Then the optical flux became constant. It is also interesting to note the rapid increase of the radio emission at MJD $=53,450$, coinciding with our epoch 3 of observations and also with the beginning of the plateau in both the optical and infrared light curves.

4. SPECTRAL ANALYSIS OF INTEGRAL DATA

We performed fits to the combined JEM-X, ISGRI, and SPI spectra for each of the four epochs (see Table 1) using XSPEC (Arnaud 1996) version 11.3. All errors quoted in this work are 90% confidence errors, obtained by allowing all variable parameters to float during the error scan. In all fits, we fixed the value of the column density to $N_{\text{H}} = 8.0 \times 10^{21}$ atoms cm$^{-2}$ as obtained by Díaz Trigo et al. (2007) using XMM-Newton data for GRO J1655–40 during the same outburst.

Our main aim in these fits is to characterize the broad continuum as seen with INTEGRAL and its wide energy coverage. To account for uncertainties in relative instrument calibrations, we fixed the JEM-X multiplicative calibration constant to 1 and let those for ISGRI and SPI free to vary in the fit for the different data sets, as shown in Table 2. In Figures 6, 7, 8, and 9 below, we show spectra from each epoch because these provide a convenient way to see the evolution of the source during our observations. We fitted the spectra with several models, and the derived parameters are presented in Table 2. We modeled the spectra with simple and phenomenological disk plus power-law models and common Comptonization models described in § 1. We find that the former are very successful (see § 4.1.1) and that there is no evidence of any spectral break in the data up to $\approx 600$ keV (see § 4.1.2). Although a simple power law provides marginally acceptable fits for the first two epochs, it was necessary to include an iron line and edge components in the fits for the last two epochs (§ 4.2).

4.1. Fits to Epochs 1 and 2

4.1.1. Fits with a Pure Power Law

We initially performed fits with a phenomenological power-law model (powerlaw in XSPEC). In the first epoch, the source spectra cover energy ranges of 5–20 keV for JEM-X and 23–600 keV for both ISGRI and SPI. In fitting the power-law model, we obtained a reduced $\chi^2$ of $\chi^2_R = 1.26$ with $\nu = 63$ ($\nu$ being the number of degrees of freedom in the fit). The presence of a multicolor disk component was not significantly required in our fit. The value obtained for the photon index is $\Gamma = 1.72 \pm 0.03$, common for black holes in a hard spectral state.

For the second epoch of observations, the source spectra extend over the energy ranges of 5–30, 23–500, and 23–400 keV for JEM-X, ISGRI, and SPI, respectively. This time, the presence of emission from a disk was significant, and we added an absorbed multicolor disk component (Mitsuda et al. 1984) to the power law [phabs (diskbb+powerlaw) in XSPEC]. We obtained $\chi^2_R = 1.38$ with $\nu = 88$. The value obtained for the inner disk temperature is $kT_{\text{in}} = 1.25 \pm 0.01$ keV. The spectrum is softer, with a photon index of $\Gamma = 2.21 \pm 0.04$.

For the last two epochs, in fitting with the phenomenological power law (plus a multicolor disk blackbody component), the spectra showed large negative residuals at $\approx 10$ keV, compatible with the presence of Fe edges. The presence of positive residuals in the 6–8 keV range is consistent with the presence of a broad Fe emission line. In § 4.2, we go into more detail about the fits for both these epochs.

4.1.2. Fits with Thermal Comptonization Models

As explained in § 1, all models involving thermal Comptonization processes as the origin of the high-energy emission seen in black hole transient systems predict an energy turnover at the electron temperature of the corona. So, in order to assess the role of Comptonization during our observations, we fitted with the thermal Comptonization model of Titarchuk (1994; comptt in XSPEC), which deals with the special case of high temperatures, small opacities, or both (so that relativistic effects are taken into account). We also performed fits using the BMC model of Ebisawa et al. (1996) (see also Titarchuk & Shrader 2002 for a comoving Comptonizing medium), which deals with the Comptonization due to bulk motion of the almost free-falling (convergent accretion) flow close to the black hole. Moreover, we fitted with a phenomenological and multiplicative model with a high-energy cutoff (highcut in XSPEC) in order to find any turnover energy in our data that could be in agreement with Comptonization’s playing the major role in the high-energy emission of GRO J1655–40.

We thus fitted the spectra from the first two epochs\(^\text{10}\) with the following models: phabs (diskbb+powerlaw)highcut (hereafter model 1), phabs (diskbb+comptt) (model 2), and phabs (bmc)highcut (model 3). In the case of the first epoch, the presence of a multicolor disk component was not significantly required. We assumed a spherical geometry for the Comptonizing medium for model 2 in all our fits.

For epoch 1, we obtained the following statistics for the three models: $\chi^2_R = 1.13, 1.17, 1.13$ ($\nu = 61, 60, 59$), respectively. We find that when fitting the data with a cutoff power law (model 1), while showing slightly better statistics, the high-energy cutoff cannot be well constrained (values between 5 and 54 keV are compatible with the data). The obtained folding energy is over 253 keV. We made separate JEM-X + ISGRI and JEM-X + SPI fits to see if a break is possible in one of the two data sets. For the former, we obtained unconstrained values for the cutoff and folding energies, in the range of 5–38 keV and over 238 keV, respectively. In the second data set there was not any break in the data either. We conclude that the cutoff features found are of instrumental origin and not physically meaningful. Thus, there is not any real cutoff in our data. This conclusion is also supported by the fact that the parameters of optical depth and electron temperature ($\tau$ and $kT_e$) when fitting with model 2 are unconstrained as well. This model clearly is not a good description of the high-energy spectrum ($\gtrsim 20$ keV). Model 3, while yielding the lowest residuals, does not allow us to constrain the values of the parameters (neither bmc nor highcut component). Thus, this model does not represent a physical description of the data. The fact that model 3 provides slightly better statistics than the power-law model described in § 4.1.1 is due to the fact that it is a convolution of both soft and hard emission components, taking into account the physical conditions in the inner region of the accretion disk.

\(^{10}\) As explained in § 4.1.1, the presence of significant residuals compatible with a broad Fe emission line, edges, and likely reflection could distort our understanding of the continuum. Thus, we do not use last two epochs in our study of the continuum models. Moreover, the spectra in these epochs do not show significant emission at high energies ($\geq 150$ keV).
### TABLE 2

**Parameters Obtained for the Best Fits of the Joint JEM-X, ISGRI, and SPI Spectra**

| Parameter | Epoch 1 | Epoch 2 | Epoch 3 | Epoch 4 |
|-----------|---------|---------|---------|---------|
| $p_{\text{over}}$ | ... | ... | ... | $4.7 \pm 0.6$ |
| $N_{\text{low}}$ (photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$) at 1 keV | ... | ... | ... | $580 \pm 60$ |
| $\Gamma$ | $0.6 \pm 0.3$ | $\approx 0$ | ... | ... |
| $\gamma_{\text{min}}$ | $1.3$ (f) | $1.3$ (f) | ... | ... |
| $\gamma_{\text{max}}$ | 1000 (f) | 1000 (f) | ... | ... |
| $L_{\text{disk}}$ | $10$ (f) | $10$ (f) | ... | ... |
| $b_{\text{disk}}/l_{\text{disk}}$ | $0.8 \pm 0.3$ | $1.2 \pm 0.6$ | ... | ... |
| $L_{\text{ph}}/L_{\text{bol}}$ | $0.8 \pm 0.1$ | $0.2 \pm 0.3$ | ... | ... |
| $\tau$ | $1 \pm 0.5$ | $4 \pm 1$ | ... | ... |
| $R (=\Omega/2\pi)$ | $0$ (f) | $0$ (f) | ... | ... |
| $kT_{\text{in}}$ (keV) | 0.5 (f) | $1.25 \pm 0.02$ | ... | ... |
| $R_{\text{in}}$ | 6 (f) | 6 (f) | ... | ... |
| $R_{\text{out}}$ | 100 (f) | 100 (f) | ... | ... |
| $kT_{\text{in}}$ (keV) | ... | $1.25 \pm 0.02$ | $1.28 \pm 0.02$ | $1.27 \pm 0.17$ |
| $N_{\text{abs}}$ [$(R_{\text{abs}}/[D(10 \text{kpc})^2 \cos \theta]$] | ... | ... | ... | ... |
| $E_{\text{abs}}$ (keV) | ... | $6.7 \pm 0.3$ | $6.7 \pm 0.9$ | ... |
| $\sigma$ (keV) | ... | $0.63 \pm 0.15$ | $0.8 \pm 0.5$ | ... |
| $N_{\text{abs}}$ (photons cm$^{-2}$ s$^{-1}$) | ... | ... | $0.017 \pm 0.008$ | $0.05 \pm 0.03$ |
| $E_{\text{edge}}$ (keV) | ... | ... | $8.64 \pm 0.20$ | $8.6 \pm 0.9$ |
| $\tau$ | ... | $0.20 \pm 0.05$ | $0.20 \pm 0.10$ | ... |
| $E_{\text{edge}}$ (keV) | ... | ... | $9.278$ (f) | $9.278$ (f) |
| $\tau$ | ... | $\leq 0.02$ (f) | $\leq 0.02$ (f) | ... |
| $\Gamma$ | ... | ... | $2.50 \pm 0.23$ | ... |
| $E_{\text{pexriv}}$ (keV) | ... | $1000.0$ (f) | ... | ... |
| $R (=\Omega/2\pi)$ | ... | ... | $\leq 0.30$ | ... |
| $\cos i$ | ... | $2.8$ (f) | ... | ... |
| $T_{\text{disk}}$ (K) | ... | $0.45$ (f) | ... | ... |
| $x_{\text{pexriv}} (=4\pi F_p/n)$ | ... | $1.2 \times 10^7$ (f) | ... | ... |
| $N_{\text{pexriv}}$ (photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$) | ... | $5000$ (f) | ... | ... |
| Instrumental Normalization Factors | ... | ... | ... | ... |

| Instrument | Epoch 1 | Epoch 2 | Epoch 3 | Epoch 4 |
|------------|---------|---------|---------|---------|
| C$_{\text{JEM-X}}$ | 1.0 (f) | 1.0 (f) | 1.0 (f) | 1.0 (f) |
| C$_{\text{ISGRI}}$ | $1.1 \pm 0.1$ | $1.0 \pm 0.1$ | $0.46^{+0.11}_{-0.15}$ | $0.39 \pm 0.14$ |
| C$_{\text{SPI}}$ | $1.4 \pm 0.1$ | $1.1 \pm 0.1$ | ... | ... |
| $\chi^2$ | 1.21 | 1.44 | 2.62 | 2.73 |
| $\nu$ | 57 | 83 | 19 | 22 |

**Notes.**—Parameters fixed in the fits are denoted by “(f).” We fixed the value of the column density to $N_{\text{H}} = 8.0 \times 10^{21}$ atoms cm$^{-2}$ as obtained in Díaz Trigo et al. (2006) using XMM-Newton data on GRO J1655−40 during the same outburst. The models used are const $\times$ $\text{pexriv}$ in epoch 1, const $\times$ $\text{edge}$ in epoch 2, const $\times$ $\text{edge}$ in epoch 3, and const $\times$ $\text{edge}$ in epoch 4 (see text for details).
We derive from fitting all these models that the high energies cannot be reproduced solely with photons that are thermally up-scattered by a Comptonizing corona. In order to take this into account, we fitted the spectrum of epoch 1 with the hybrid Comptonization model EQPAIR (Coppi 2000), which is appropriate for very hot plasmas. This model describes the physics and emission properties of hybrid plasmas, where the particle energy distribution is approximately a Maxwellian plus a power law. The model treats a hot plasma cloud, mainly modeled as a spherical corona around the compact object, illuminated by soft thermal (Maxwellian) and nonthermal (either power-law or monoenergetically distributed) electrons that lose energy by Compton, Coulomb, and bremsstrahlung interactions. This model was shown to be successful in accounting for the high-energy spectra of Cygnus X-1 and other black hole candidates in different spectral states and over a broad energy band, ranging from soft X-rays to gamma rays (see, e.g., McConnell et al. 2000, 2002; Cadolle Bel et al. 2006; Malzac et al. 2006).

For epoch 2 of our observations, we obtained the following statistics for the three models: $\chi^2 = 1.47, 1.45, 2.07$ ($\nu = 86, 87, 86$), respectively. Again, model 1 does not show a break or cutoff below 500 keV (i.e., the values of both cutoff and folding energies cannot be constrained), and model 3 is not a proper fit to the data, because of the bad statistics. In this epoch, the values obtained for the optical depth of the Comptonizing medium and the temperature of the electrons ($\tau$ and $kT_e$) cannot be constrained. Thus, the data show that thermal Comptonization is not the main process generating the emission at high energies ($\gtrsim 20$ keV). As in epoch 1, we tested the model of Coppi (2000) optimized for very hot corona (see description in the previous paragraph), this time coupled with a diskbb component to describe the soft emission from the accretion disk.

4.1.3. Fits with the EQPAIR Nonthermal Comptonization Model

The EQPAIR model takes into account angle dependence, Compton scattering (up to multiple orders), photon pair production, pair annihilation, and bremsstrahlung, as well as reflection from a cold disk. As noted by Coppi (2000), if a spectrum extends up to 500 keV, high-energy emission from a nonthermal population of electrons is clearly present.

As can be seen in Figures 4 and 5, showing fits of both epochs 1 and 2 with a single power law (see description in §4.1.1), a small deficit of counts in the ISGRI spectra (red) above 200 keV with respect to SPI (green) is clearly present. Moreover, the large bins of the ISGRI spectra in this range indicate that the source was not detected above 200 keV. This could be a consequence of the fact that SPI is optimized for spectroscopy up to 1 MeV, while ISGRI has poorer sensitivity above 200 keV. Taking these considerations into account, we limit our analysis of the ISGRI data to the energy range 23–200 keV.

The EQPAIR model allows one to inject a nonthermal electron distribution with Lorentz factors between $\gamma_{\min}$ and $\gamma_{\max}$ and a power-law spectral index $\Gamma_p$. The cloud is illuminated by soft thermal photons emitted by an accretion disk. These photons serve as seeds for Compton scattering by both thermal and nonthermal electrons. The system is characterized by the power (i.e., luminosity) $L_i$ supplied by its different components. We express each of them dimensionlessly as a compactness parameter, $l_i = L_i/\sigma_T(Rmec^3)$, where $R$ is the characteristic dimension and $\sigma_T$ is the Thomson cross section of the plasma. Thus, $l_x, l_h, l_{nth}$, and $l = l_h + l_{nth}$ correspond to the power from the soft disk entering the plasma, thermal electron heating, electron acceleration, and the total power supplied to the plasma. The total number of electrons (not including $e^+e^-$ pairs) is determined by $\tau$, the corresponding Thomson optical depth, measured from the center to the surface of the scattering region. We considered the source to be moderately compact and fixed $l = 10$, as broadly reported for other sources with similar characteristics.

The disk spectrum incident on the plasma is modeled with a multicolor disk blackbody as given by the diskbb model in XSPEC (Mitsuda et al. 1984). The temperature of the inner edge of the accretion disk was fixed to $kT_x = 0.5$ keV. The limits of the accretion disk were fixed at $R_{\max} = 100 R_g$ and $R_{\min} = 6 R_g$. We attempted to fit the spectra of both epochs 1 and 2, fixing the reflection covering factor to zero.

For epoch 1 of our observations, we first performed a fit with nonthermal electrons injected with a power-law distribution of Lorentz factors from $\gamma_{\min} = 1.3$ to $\gamma_{\max} = 1000$. The upper and lower limits $\gamma_{\min}$ and $\gamma_{\max}$ were kept fixed while fitting the power-law index $\Gamma_p$. This resulted in an acceptable fit, with $\chi^2 = 1.21$ ($\nu = 57$). The unfolded broadband spectrum and residuals are shown in Figure 6. The best-fit parameters are presented in Table 2; $l_h/l_x$ is about unity, that is, intermediate between what is found in the hard state (4–10) and the thermal-dominant state ($\lesssim 0.4$) (Ibragimov et al. 2005). The heating of the plasma is dominated by the nonthermal acceleration ($l_{nth}/l_h \approx 1$). We also fitted the spectra of this epoch considering a monoenergetically distributed...
population of nonthermal injected electrons instead. The reduced $\chi^2$ thus obtained is slightly better ($\chi^2 = 1.19$, $\nu = 57$). The values obtained for $l_b/l_e$ and $l_{\text{nth}}/l_b$ remained unchanged, except for an increase in the Thomson scattering depth (from $1.0 \pm 0.6$ to $2.7 \pm 0.4$). The increase in the optical depth lends support to the scenario of Comptonization through injected nonthermal electrons being the dominant mechanism, in the sense that if this is done by electrons with a monoenergetic distribution, then having a denser cloud would produce the same effect as taking into account a broader distribution (both in energy and spatially). Thus, we conclude that in order to reproduce the spectrum of epoch 1, we have to consider an almost pure distribution of nonthermal accelerating particles.

As in epoch 1, we tested the model of Coppi (2000) optimized for very hot coronae in the observations of epoch 2, this time coupled with a diskbb component to describe the soft emission from the accretion disk. We performed a fit with nonthermal electrons injected with a power-law distribution of Lorentz factors from $\gamma_{\text{min}} = 1.3$ to $\gamma_{\text{max}} = 1000$. The upper and lower limits $\gamma_{\text{min}}$ and $\gamma_{\text{max}}$ were kept fixed while fitting the power-law index $\Gamma_p$. This resulted in an acceptable fit, with $\chi^2 = 1.44$ ($\nu = 83$). The unfolded broadband spectrum and residuals are shown in Figure 7. The best-fit parameters are presented in Table 2; $l_b/l_e$ is again about unity. However, the heating of the plasma by nonthermal particles is practically nil ($l_{\text{nth}}/l_b \approx 0$). The situation does not improve if one considers a monoenergetic distribution of the nonthermal accelerated electrons. This is not surprising, since as claimed by Coppi (2000), a very good spectrum extending above 200 keV is mandatory in order to disentangle a likely population of nonthermal particles in the source. In the case of our observations, the large bin at $\approx 200$ keV shows that the source was not detected above this energy. We conclude that while in epoch 2 of our observations a break is not observable in the high-energy data ($\approx 20$ keV), the energy coverage is not great enough to test for the presence of nonthermal processes. This is due to the fact that in this period the spectrum became very soft, as compared with epoch 1, with radiation detected to $\approx 200$ keV as most.

4.2. Fits to Epochs 3 and 4

4.3. Fits with Iron Emission Line and Absorption Edges

As can be seen from the shape of the residuals (Fig. 8), fits with the simple multicolor disk model of Mitsuda et al. (1984) and a power law do not yield formally acceptable fits to the last two epochs. The presence of large residuals at 6–8 keV and around 10 keV require us to take into account an iron emission line, iron absorption edges, and likely disk reflection components. These features are theoretically required in very ionized mediums such as the close vicinity of a black hole (see Ueda et al. 1998 for a prior detection of Fe absorption lines and edges in GRO J1655–40 in the context of observations of the 1996 outburst, and George & Fabian 1991 and Laor 1991 for a description of the Fe line profile produced in accretion disks around black holes). The reflection component takes into account the physics due to the continuum produced by a source of hard X-rays Compton-reflected by an accretion disk (Gilfanov et al. 2000).

We fitted our spectra with the following XSPEC model: phabs (diskbb+powerlaw+gaussian)edge+edge. The results and the folded and unfolded spectra are shown in Table 2 and in Figures 9 and 10, respectively. Regarding the Gaussian Fe emission line component, we constrained the line center to lie at 6.4–6.97 keV, which is the allowed range by the different ionization states of Fe. Also, we constrained the width ($\sigma$) of the emission line to be 1 keV as a fiducial maximum value in order to obtain convergence of our fits. Regarding the two iron absorption edges, one was fixed at 9.278 keV, which corresponds to Fe xxvi and is expected to appear, given the likely range of temperatures and ionization.
Fitting this model to the spectra for epochs 3 and 4 we obtained better results than fitting with a power-law model (plus an absorbed multicolor disk), that is, \( \chi^2 = 9.99 \) with \( \nu = 21 \) and \( \chi^2 = 2.73 \) with \( \nu = 22 \) for the third and fourth epochs, respectively. Although the fit was unacceptable for epoch 3, because of large residuals around \( 10-20 \) keV, which could be due to reflection,\(^{11} \) the fit was reasonable for epoch 4. The multicolor disk component gave an inner disk temperature of \( kT_{\text{in}} = 1.27 \pm 0.17 \) keV for the fourth epoch, for which we also obtained a very soft photon index (\( \Gamma = 4.7 \pm 0.6 \)).

We substituted the pexriv reflection model for the power-law component for the third epoch. This is a power law with an exponential cutoff to take into account reflection effects in the spectrum. In fitting with pexriv, we imposed an overabundance of Fe of \( 2.8 \) with respect to the solar value and \( \cos i = 0.45 \), the latter implying an inclination of \( 63^\circ \) for the reflection medium, namely, the disk (as found by Diaz Trigo et al. 2007 based on XMM-Newton and INTEGRAL data for the same period of observation). The disk temperature that produced the smallest residuals was \( T_{\text{disk}} = 1.2 \times 10^7 \) K, so we fixed this value in our fits. This value is consistent with having very ionized material in the accretion disk. Also, in order to properly fit the high-energy part of the spectrum (\( \gtrsim 20 \) keV), it was necessary to fix the pexriv e-folding energy to a very high value, namely, \( 1000 \) keV, implying a nondetection of any cutoff up to \( \approx 200 \) keV. As a result of this fit for epoch 3, we obtained a reflection covering factor of \( R \leq 0.3 \). Actually, this quantity \( (R) \) approximately measures the solid angle subtended by the reflecting medium as seen from the source of the primary radiation, \( R \approx \Omega_{\text{ref}}/2\pi \), so that \( R = 1 \) for an isotropic point source above an infinite, optically thick slab. We fixed the ionization parameter to a very high value, consistent with a highly ionized medium, \( x_i = 4\pi F_{\text{ion}}/n = 5000 \) ergs cm\(^{-3}\) s\(^{-1}\) (where \( F_{\text{ion}} \) is the \( 5-20 \) keV irradiating flux and \( n \) is the density of the reflector; see Done & Nayakshin 2001).

In order to estimate the source luminosity in each of our observations, we used a power law plus an absorbed multicolor disk to model all the epochs. The contribution of the iron emission and absorption effects together only account for less than 10% of our data in the last two epochs. The unabsorbed flux in the \( 5-100 \) keV energy range, \( F_X(5-100) \), is \( 1.4 \times 10^{-9} \), \( 1.2 \times 10^{-9} \), \( 1.0 \times 10^{-8} \), and \( 1.0 \times 10^{-8} \) ergs cm\(^{-2}\) s\(^{-1}\) for epochs 1–4, respectively. For a distance of \( 3.2 \) kpc (Tingay et al. 1995), these fluxes give luminosities in the \( 5-100 \) keV energy range, \( L_X(5-100) \), of \( 1.7 \times 10^{36} \), \( 1.5 \times 10^{37} \), \( 1.2 \times 10^{37} \), and \( 1.2 \times 10^{37} \) ergs s\(^{-1}\). The unabsorbed fluxes in the \( 5-600 \) keV energy range are \( F_X(5-600) \) = \( 3.7 \times 10^{-9} \), \( 1.2 \times 10^{-9} \), \( 1.0 \times 10^{-8} \), and \( 1.0 \times 10^{-8} \) ergs cm\(^{-2}\) s\(^{-1}\), giving luminosities of \( L_X(5-600) \) = \( 4.6 \times 10^{36} \), \( 1.5 \times 10^{37} \), \( 1.2 \times 10^{37} \), and \( 1.2 \times 10^{37} \) ergs s\(^{-1}\) for epochs 1–4, respectively. Even if we take the broader energy range as more indicative of the true source luminosity, these values represent only 0.5%, 1.5%, 1.3%, and 1.3% of the Eddington limit \( L_{\text{Edd}} = 9.4 \times 10^{38} \) ergs s\(^{-1}\) for a black hole of \( 7 M_\odot \), respectively.

5. DISCUSSION AND CONCLUSIONS

We have performed fits to four epochs of INTEGRAL broadband spectra of the stellar-mass black hole GRO J1655−40 during its 2005 outburst. We find that GRO J1655−40 was in the hard state in the first epoch, based on a low photon index (i.e., \( 1.72 \pm 0.03 \)) and the absence of a strong thermal disk component. The source evolved to a state that resembles the thermal-dominant state, in the classification scheme of Remillard & McClintock (2006). These results are in agreement with the previous study of this outburst by Brocksopp et al. (2006). However, Saito et al. (2007), on the basis of their analysis of RXTE PCA data for this source, showed that the luminosity of the accretion disk deviates from the \( L \propto T^4 \) relation typical of thermal-dominant states during our other three observations (epochs 2, 3, and 4). So, the state observed may not be a true thermal-dominant state, or nonthermal effects may need to be modeled to describe the accretion disk’s emission (Kubota et al. 2001).

For the two later epochs, we found that our data are best fitted by adding an iron emission line and edges to the model, consisting of an absorbed multicolor disk (Mitsuda et al. 1984) plus a power-law component. Although the obtained fits were not formally acceptable (\( \chi^2 \) of 9.99 and 2.73 for epochs 3 and 4, respectively), the fit in the fourth epoch was improved by \( \Delta \chi^2 = 4.8 \). Also, the shape of the residuals using the model consisting of a multicolor disk blackbody plus a power law shows a clear excess in the \( 6-8 \) keV range and a drop around \( 10 \) keV, features that can only be explained by the presence of an iron emission line and Fe edges. The spectrum in the third epoch shows an excess of absorption in the \( 10-20 \) keV energy range with respect to that

\(^{11} \) It is important to note that Diaz Trigo et al. (2006) did not find reflection signatures in their analysis of joint XMM-Newton and INTEGRAL data corresponding to our fourth epoch. The disagreement could be due to the \( 20-30 \) keV bin removed from their study, a change made in order to improve the statistics for the joint spectrum obtained in this period.
expected taking into account the edges obtained in Diaz Trigo et al. (2007) based on XMM-Newton and INTEGRAL spectra (see § 4.2). This excess could be explained by the presence of reflection, but the situation is still unclear. We attempted to deal with this feature in epoch 3 by fitting with a broken power law model (pexriv in XSPEC), but there is no clear evidence for a break in this spectrum. We conclude that for GRO J1655−40, it is difficult to study reflection features. This may be due to the high inclination of the source, which could alter the shape of such features through scattering. The presence of these features in the spectra of epochs 3 and 4 may reveal differences in the disk outflow properties with respect to any outflow in epochs 1 and 2. In fact, our spectrum obtained in epoch 3 precedes a Chandra observation revealing a line-rich spectrum (Miller et al. 2006) by only 3 days.

Assuming a value of 63° for the inclination (Diaz Trigo et al. 2007) and a distance of 3.2 kpc (Tingay et al. 1995), the disk normalization factor (in fits made only with a power-law model plus a multicolor absorbed disk) gives an inner disk radius\(^{12}\) of 16.5 ± 0.2 km for the second epoch (the first epoch was in a hard state and had no significant contribution from the disk, as shown in § 4.1.1). Since \(R_g = 10.4\) km is the value of the gravitational radius for a 7 \(M_\odot\) black hole, we find that the matter arrives at an inner radius of \(\approx 1.6 R_g\) in the second epoch. This value is consistent with the value predicted for a maximally rotating black hole, as explained in § 1 (\(R_{\text{ISCO}} = 1.25 R_g\)), and is similar to that obtained by Tomsick et al. (1999). By analyzing RXTE data, Tomsick et al. found inner radius values \(R_{\text{in}}\) of 10.9 ± 2.6 to 21.9 ± 5.2 km, depending on the value adopted for the disk inclination. Of course, values of the inner disk radius inferred from continuum fits are suspect and must be viewed with caution. A number of effects (Merloni et al. 2000) can serve to distort the observed inner disk parameters (see Saito et al. 2007 for a determination of more realistic values for the radii, since these are not affected by a strong power-law component). According to Merloni et al. (2000), the main effect seems to be that the opacity is dominated by electron scattering rather than free-free absorption. The net result is that the derived temperature given by the parameter \(kT_{\text{in}}\) overestimates the effective inner temperature by a factor of 1.7 or more (Shimura & Takahara 1995).

The most interesting issue regarding our INTEGRAL observations of GRO J1655−40 is undoubtedly the presence of very significant and unbroken high-energy emission up to 500 keV in the hard state of GRO J1655−40, as noticed from the first epoch. Grove et al. (1998) made a comparative measurement of a number of systems with data from the OSSE instrument on CGRO and

\[^{12}\text{This radii are measured from infinity, using the formula } R_{\text{in}} = D(d\text{d} + \text{bb}_{\text{com}})/ \cos i, \text{ where } R_{\text{in}} \text{ is in kilometers and } D \text{ is in units of 10 kpc. This formula is inferred without taking into account effects from general relativity. If gravitational corrections were taken into account, a smaller comoving radius would be obtained.} \]
found that many of these systems showed a cutoff at high energies around ~100 keV in the hard state.13 Since then, several studies have tried to measure cutoffs in the spectra, which could manifest the validity of Comptonization by thermal electrons playing the major role in the high-energy emission of black holes in the hard state. In our work we did not find such a break, and the presence of a nonthermal population of relativistic electrons was inferred from the fitting of our spectrum in the hard state.

Our finding is that nonthermal processes are the most important in explaining the high-energy emission of the hard state of GRO J1655−40. In addition, there is not any break in the data indicating that the high-energy emission is mainly produced by thermal Comptonization, as previously claimed. Moreover, nonthermal Comptonization is the main source of the high-energy emission in the second epoch (thermal-dominant state). This condition for the thermal-dominant state has been broadly reported in the literature since Grove et al. (1998).

In Table 3, we summarize the references showing breaks in the high-energy emission of several black hole candidates in the hard and intermediate states. One contemporaneous study by Shaposhnikov et al. (2007) of the hard state of GRO J1655−40 used INTEGRAL observations covering a period of time slightly prior to that of our first epoch. They pointed to the reading of a cutoff around 200 keV in their ISGRI and SPI spectra as a manifestation of thermal Comptonization’s being the main source of the high-energy emission. However, their sensitivity at energies ≥200 keV is not high enough to disentangle the emission of a nonthermal population of electrons. As also noted by Coppi (2000), if a spectrum extends up to 500 keV, high-energy emission from a nonthermal population of electrons is clearly present. The finding of such a contribution in the high-energy emission has been reported before for the Cyg X-1 system (Malzac et al. 2006; Cadolle Bel et al. 2006 [both in the intermediate state], and it may be present in GRS 1915+105 (Zdziarski et al. 2001; Rodriguez et al. 2004 [both in the thermal-dominant state]). With our study, we extend the list of sources showing high-energy emission from nonthermal electrons with GRO J1655−40, this time in the hard state. Joinet et al. (2007) also reported the detection of a nonthermal population of electrons in the hard state of GX 339−4. However, they also indicated the presence of a cutoff in the spectrum.

From Table 3, it can be seen that while some cutoffs appear to be close to the upper boundaries of the high-energy instruments used, others appear to be physically meaningful. The latter correspond to the systems GX 339−4 and Cyg X-1, both having known low inclinations angles of i ≈ 45° and i ≈ 35°, respectively. GRO J1655−40 is a very high inclination system, with an inner disk that could have an inclination of i = 85° (see § 1). Comptonization of soft photons through thermal and/or nonthermal electrons seems to be highly isotropic to an observer external to the system if the electrons do not acquire outflow velocities v/c ≥ 0.2 (Beloborodov, 1999), so in principle this should not depend on the inclination angle of the system. But other processes, such as reflection, could depend on the viewing angle, being almost unobserved for high-inclination systems such as GRO J1655−40 (as pointed out above with our fitting of epoch 3). So, GRO J1655−40 in the hard state would be an excellent source for the study of Comptonization processes, without any apparent disturbance from other high-energy mechanisms (including soft emission from a disk). If these hypotheses are correct, we would have discovered that Comptonization of black hole transients in the hard state occurs mainly through nonthermal relativistic electrons. This conclusion is also supported by the study of Malzac et al. (2006) of Cyg X-1 in the intermediate state, because, while they found a high-energy cutoff around 100 keV, they also point to the presence of high-energy emission from a nonthermal population of electrons in a state close to the hard state (in the case of Joinet et al. 2007, in the hard state of GX 339−4).

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### Table 3

| Source      | State | $\Gamma$ | $E_{\text{cutoff}}$ (keV) | $E_{\text{max}}$ (keV) | $T_x$ (keV) | Reference |
|-------------|-------|----------|-----------------|-----------------|-------------|-----------|
| IGR J17497−2821 | LH    | 1.67 ± 0.06 | 195 ± 50 | ≈200 | 35±200 | 1.45±0.5 | 1 |
| GX 339−4       | LH    | 1.4−1.6 | 50−200 | ≈200 | ... | ... | 2 |
|              | IS    | 1.92 ± 0.05 | 72 ± 8 | ≈200 | ... | ... | 3 |
| XTE J1550−564  | LH    | 1.70 ± 0.01 | 115 ± 5.6 | ... | ... | ... | 4 |
|              | IS    | 1.53 ± 0.01 | 460 ± 300 | ... | ... | ... | 4 |
| Cyg X-1       | LH    | 1.9 ± 0.1 | 150 | ≈600 | 67±8 | 1.98 ± 0.22 | 5 |
|              | IS    | 2.1 | 165−2.0 | ≈100 | ≈1000 | 20−65 | 0.55−1.36 | 6 |
| GRO J1655−40  | LH    | 1.35 ± 0.03 | 100−200 | ≈600 | ... | ... | 8 |
|              | LH    | 1.72 ± 0.03 | 100−200 | ... | ≈500 | ... | 9 |

**Note:** Values are listed for several sources in several states close to the hard state. Also, values for the high-energy cutoffs and/or break energies (if present) are reported.

**References:**
1. Walter et al. 2007; 2. Miyakawa et al. 2007; 3. Belloni et al. 2006; 4. Yuan et al. 2007; 5. Cadolle Bel et al. 2006; 6. Malzac et al. 2006; 7. Wilms et al. 2006; 8. Shaposhnikov et al. 2006; 9. This work.

13 OSSE integration times were very long (on the order of weeks), so different states would be mixed. This is not an issue for INTEGRAL, since exposures for each obtained spectrum are around 2 days and noticeable high-energy evolution is not expected with this timing, as inferred from the light curves.
