OSSE Observations of NGC 4151

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Abstract

We report results of a two-week observation of the Seyfert galaxy NGC 4151 with the Oriented Scintillation Spectrometer Experiment (OSSE) instrument on the *Compton* Gamma Ray Observatory (GRO). The source had a very soft spectrum which is best represented by a broken power law or Sunyaev-Titarchuk thermal Comptonization model. It can be characterized by an exponential shape with an e-folding energy of 39 ± 2 keV in the energy range 65 – 300 keV, and an intensity at 100 keV of $(2.33 \pm 0.05) \times 10^{-5}$ photons cm^{-2} s^{-1} keV^{-1}. Source intensity variability of $\sim$ 25% was observed during the 14 days of our observations; no significant change in spectral shape was detected for this period. The steepness and shape of the spectrum above 100 keV rule out (χ^2 probability $\sim 7 \times 10^{-4}$) simple pair cascade models in a compact source which have been suggested for Seyfert galaxies.

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1 Introduction

NGC 4151, the archetype of Seyfert (Sy) 1 galaxies (actually characterized as Sy 1.5) and the nearest object of its class (d= 20 Mpc, assuming $H_0 = 50$ km s^{-1}Mpc^{-1}), has been the object of various campaigns at all wavelengths. It is also one of the four Active Galactic Nuclei (AGN) detected significantly prior to GRO at energies above 100 keV (the others are 3C 273, Cen A and MCG 8-11-11; see Bassani and Dean 1983). The study of this high-energy emission is important for understanding the processes occuring in the central regions of AGN, which are assumed to contain supermassive black holes (Rees 1984). It is also crucial to establish whether there is a canonical AGN spectrum in this energy range, as has been found for Seyfert 1 galaxies below 100 keV, and to determine whether AGN as a class can make up the cosmic X-ray background (CXRB) by the superposition of large numbers of such sources.

The current observations represent the most sensitive observation of NGC 4151 to date in this energy range, and provide important new information for constraining models which predict hard emission above several hundred keV. Previous high-energy observations of NGC 4151 have detected power law spectra with photon indices $\alpha \sim 1.7$, sometimes up to MeV energies (for a review see Perotti et al. 1991). The fastest variability observed so far in NGC 4151 is on the order of 0.5 days (e.g. Lawrence 1980) in the $2 - 10$ keV energy band. Only long-term variability has been reported for energies above 100 keV (Perotti et al. 1991).

2 Instrumentation

The Oriented Scintillation Spectrometer Experiment (OSSE) is one of four experiments on NASA's Arthur Holly Compton Gamma Ray Observatory (GRO) satellite (Johnson et al. 1993). OSSE was designed to undertake γ-ray observations of astrophysical sources in the $0.05 - 10$ MeV range. OSSE consists of four identical detector systems with independent, single-axis orientation controls which provide an orientation range of 192 degrees. The primary detecting element for each detector is a large-area NaI(Tl) scintillation crystal (13 in. diameter by 4 in. thick) shielded in the rear by an optically coupled 3-in. thick CsI(Na) scintillation crystal in a "phoswich" configuration. Each phoswich is actively shielded by a 3.3-in. thick annulus of NaI(Tl) scintillation crystals and passively collimated by a tungsten slat collimator which defines a $3.8^\circ \times 11.4^\circ$ full width at half maximum (FWHM) gamma-ray aperture of the phoswich detector. The total aperture area of the four detectors is 2620 cm^2, with an effective photopeak area at 511 keV of 2000 cm^2. These characteristics result in an OSSE continuum sensitivity (3σ) of $\sim 1.2 \times 10^{-3}$ photons cm^{-2} s^{-1} MeV^{-1} (at 100 keV for 5×10^5 seconds of observation).

OSSE observations consist of a sequence of two-minute observations of a source field alternated with 2-min. offset-pointed background measurements. The 2-min. duration is selected to be short relative to the typical orbital background variations. When possible, source-free fields 4.5° offset on both sides of the source position along the detector scan plane are used for background observations. For the observation of NGC 4151, special care was taken to verify that the nearby Sy 1 galaxy, NGC 4051, which was in the field of view of one background field, did not contribute significantly to the background estimates. This was achieved by selecting an additional background field offset 8° from NGC 4151 and comparing background subtraction results from the three different fields. No significant contribution of NGC 4051 was found by this method; an upper limit on the NGC 4051 emission in the

$60-120$ keV band is placed at 7% of the flux from NGC 4151. Data screening selected only the highest quality data of both source and background observations. Background estimation was achieved by performing a quadratic fit to three or four (where possible) contiguous two-minute background accumulations of satisfactory data quality in close temporal vicinity on both sides of every two-minute accumulation of NGC 4151. A more detailed description of OSSE performance and spectral data analysis procedures can be found in Johnson et al. (1993).

3 Observations and Results

OSSE observed NGC 4151 in the energy range 65 keV$-$10 MeV during the period from 1991 June 28 to July 12. A total on-source observation time for the sum of four detectors of 8.6×10^5 seconds of screened data were used in the analysis. A similar amount of time background observations were used. The source was detected at a significance level of greater than 10σ per day in the energy range $80-150$ keV; significant positive flux is observed in the average spectrum to 300 keV. Figure 1 shows the average daily intensities for the sum of all four detectors in the energy range $80-150$ keV. The flux in this band is seen to vary by $\sim 25\%$ during the observation. The χ^2 per degree of freedom for the hypothesis of constant source flux is 4.4. During this variation in intensity, no significant change in spectral shape was observed. An exponential fit to the seven days with the lowest intensity indicated an e-folding energy of 40 ± 2 keV while a similar fit to the most intense days indicated 39 ± 2 keV. The average spectrum accumulated over the 14-day observation was binned into 132 equally spaced energy channels from $65-800$ keV. The results of spectral fitting in this energy band are shown in Table 1. The errors given in this table and the remainder of the paper are the 68% confidence limits for joint variation of the respective parameters of interest. Upper limits are displayed at the 2σ level.

OSSE observed a very soft spectrum from NGC 4151 which is well described by an exponential model of the form:

$$\Phi(\mathrm{E}) = (2.33 \pm 0.05) \times 10^{-5} \exp\left(\frac{100 - \mathrm{E(keV)}}{39 \pm 2}\right) \text{ photons cm}^{-2}\mathrm{s}^{-1}\mathrm{keV}^{-1}.$$

A spectral fit with a single power law, which yields a photon index of 2.72 ± 0.07, does not give a satisfactory result. The χ^2 probability for this model is 5×10^{-4}. A broken power law fit gives a photon index of $\alpha_1 = 2.1 \pm 0.3$ below 103^{+12}_{-9} keV and $\alpha_2 = 3.4^{+0.3}_{-0.4}$ above that energy (χ^2 probability = 0.21). A satisfactory fit can also be achieved by a more physical model such as thermal Comptonization of soft photons (Sunyaev & Titarchuk 1980). This model gives a plasma temperature of 37^{+10}_{-6} keV and optical depth of $2.7^{+1.0}_{-0.7}$ (χ^2 probability = 0.11). Figure 2 shows the Sunyaev-Titarchuk and the power law fits to the OSSE data.

The OSSE spectrum shows NGC 4151 in an extremely soft state which, contrary to previous, less sensitive observations, cannot be described by a single power law. A spectrum as steep as the one observed here has been observed only once before: the GRANAT instruments, ART-P and SIGMA, recently found a hard spectrum from $3 - 30$ keV ($\alpha = 1.44 \pm 0.03$, Apal'kov et al. 1992) together with a steeper spectrum from $50 - 300$ keV ($\alpha = 3.1^{+1.1}_{-0.9}$, Jourdain et al. 1992). A softening of the spectrum was also reported from one of three HEAO-1 observations (Baity et al. 1984) at energies above $\sim$ 50 keV. In contrast, hard power law spectra ($\alpha \sim 1.5$) at energies up to $\sim$ 100 keV have been reported for NGC 4151 from balloon and satellite observations on several occasions (for a review see Perotti et al. 1991). The MISO balloon experiment (Perotti et al. 1981) has observed this hard power law extending to energies of several MeV. The OSSE data are compared with the Ginga/HEXE (Maisack & Yaqoob 1991), SIGMA results (Jourdain et al. 1992) and MISO balloon observations at MeV energies (Perotti et al. 1981) in Figure 3. It is possible that NGC 4151, or Seyfert galaxies in general, have both hard and soft spectral states in this energy range. Due to lower sensitivities of previous instruments the soft state may have escaped earlier detection.

The comparision of the OSSE observation of 1991 and the MISO result of 1979 indicate a variability above 400 keV by a factor of $10 - 30$ in contrast to the variability in the $2 - 10$ keV range by ~ 6.

4 Discussion

By studying a sample of active galaxies (primarily Sy 1s) with HEAO-A4, Rothschild et al. (1983) found that Seyfert galaxies have a canonical spectral shape between 2 and 100 keV, described by a power law with photon index $\alpha \sim 1.7$. A similar conclusion was obtained from EXOSAT Seyfert spectra ($2 - 10$ keV) by Turner & Pounds (1989). Recent observations by Ginga, however, have shown that the X-ray spectra of Seyfert galaxies are generally more complex. A hard shoulder above 10 keV in Ginga spectra of Seyferts (e.g. Pounds et al. 1990) has been interpreted as evidence for Compton reflection of an incident power law spectrum from a layer of cold material, presumably an accretion disk (e.g. White, Lightman and Zdziarski 1988). No evidence for such a component has been found in NGC 4151 (Maisack & Yaqoob 1991, Weaver et al. 1992).

As discussed by Rothschild et al. (1983), the sum of the assumed canonical power laws from unresolved AGN would provide a diffuse flux greater than that observed at energies above a few hundred keV. The softening or break at ~ 100 keV in the spectrum of NGC 4151 in this observation, if assumed to be typical of all AGN, removes this potential excess and suggests that the composite AGN spectrum could be more in line with the observed diffuse background power law, $\alpha \sim 2.8$, in the $100 - 500$ keV band (e.g. Gruber et al. 1985). This state of NGC 4151, as observed by OSSE and perhaps SIGMA, could well be the nominal state and the hard emission observed by MISO into the MeV region could be a transient or less frequent state. More observations of NGC 4151 during the GRO mission will show whether there are two distinct spectral states.

Previous observations have shown that the X-ray emission from most Seyferts, including NGC 4151, follows a luminosity-spectral index correlation in which the spectrum becomes steeper or softer as the source brightens (Yaqoob & Warwick 1991). The spectral index varies between 1.3 and 1.7 in the $2-20$ keV band for NGC 4151. One popular model for explaining the $2-10$ keV emission involves nonthermal pair cascades (e.g. Lightman & Zdziarski 1987). In such pair models, the X-ray spectrum is generated by Compton-upscattering of soft UV photons from the "blue bump" by relativistic electrons and has a power law shape. The photon density above 511 keV in the emitting region can be so high that secondary electron-positron pairs are produced by photon-photon interactions. These secondary $e^{\pm}$ pairs also scatter a significant portion of the primary radiation. The effect of these pair cascades is a steepening of the X-ray spectrum with increasing luminosity. The pairs lose most of their energy by scattering, rather than escaping, and form a thermal pair region. Annihilation of these pairs produces a broad feature at 511 keV.

At photon energies above $m_e c^2/\tau^2$, where τ is the optical depth of the pair plasma, Compton downscattering removes photons causing the emerging spectrum to steepen by $\Delta\alpha \sim 1$ above the energy of $m_e c^2/\tau^2$ (Ghisellini 1989). Fitting this spectral shape to the OSSE data implies a large optical depth, $\tau = 2.7$; the unmodified power law below the energy $m_e c^2/\tau^2$ (and the OSSE energy range) has a best fit spectral index of 2.37. The fit is unacceptable with a χ^2 probability of 0.01. Fixing the original index in this model to the "canonical" Seyfert power law index of $\alpha = 1.7$, as observed simultaneously by Ginga (Yaqoob et al. 1993), and forcing the turnover to occur somewhere between the Ginga and OSSE energy range does not give an acceptable fit (χ^2 probability $= 7 \times 10^{-4}$).

Coppi & Zdziarski (1992) have successfully applied a pair model which includes reprocessing off cold material to NGC 4151 for two differing spectral states of the source observed in X-rays and gamma rays by Ginga/HEXE in 1987 and by GRANAT in 1990. In both states, the model predicts a broad feature at 511 keV which would be easily detected by OSSE in

1991. A pair temperature of ~ 30 keV creates an annihilation feature of width ~ 120 keV. The OSSE data are inconsistent with annihilation features of the intensity predicted by Coppi & Zdziarski. The addition of an annihilation feature to the OSSE exponential continuum models produces an insignificant best fit 511 keV flux of $(0.2 \pm 4) \times 10^{-5}$ photons cm^{-2} s^{-1}. The 99.5% confidence limit for a broad 511 keV emission feature (modeled as a gaussian with 150 keV full width at half maximum) in addition to the observed continuum is 9.6×10^{-5} photons cm^{-2} s^{-1} for exponential continuum and 4.4×10^{-5} photons cm^{-2} s^{-1} for the best fit single power law. The limit is somewhat dependent on the assumed width of the feature, varying by $\sim 10\%$ for widths between $100 - 200$ keV. Figure 4 shows the Coppi and Zdziarski models for NGC 4151 in relation to the OSSE results. In general, the hard X-ray emission of the pair cascade models is not soft enough to be consistent with the OSSE spectrum in the $150 - 300$ keV range. The flux ratio $(300 - 1000$ keV$)/(60 - 300$ keV$)$ observed by OSSE is at least 6 times smaller than that in any of the models of Lightman & Zdziarski (1987). The absence of any feature at 511 keV at the sensitivity limit of the OSSE observation is not in accord with the pair annihilation signature predicted by simple pair cascade models.

As shown above, the simplest thermal Comptonization models (Sunyaev & Titarchuk 1980; Katz 1976) provide an acceptable fit to the NGC 4151 data measured by OSSE. In such models, the $2 - 10$ keV spectral index/luminosity correlation results from variations in the soft photon flux (e.g. Dermer 1990). This is because an increase in the number of soft photons reduces the temperature of the thermal electrons, thus causing a spectral enhancement and softening at X-ray energies. The soft photons could be UV radiation from a cool outer blackbody disk which is reprocessed by the inner hot electron cloud (Wandel & Liang 1991). The onset of pair production at temperatures of several hundred keV limits the maximum temperature of the emission region in thermal models to $1 - 2$ MeV (Svensson 1984; Dermer 1989). Thus the confirmation with future OSSE observations of the intense gamma radiation extending to 10 MeV, as measured earlier from NGC 4151 by the MISO experiment, would provide a crucial test for thermal models.

5 Summary

OSSE has observed NGC 4151 to have a continuum spectrum which steepens exponentially with an e-folding energy of 39±2 keV. Simple pair models cannot explain the observed spectrum, and the pair annihilation feature predicted by such models is not seen in the OSSE data. Repeated observations of this object, and Seyfert galaxies in general, with the high sensitivity provided by OSSE are required to determine whether this spectral shape is common or is even the dominant spectral state in this class of AGN.

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Model	χ^2 Prob	I^a	α	α_2	E_{Br}	kT	τ
Power Law (PL)	5×10^{-4}	2.11 ± 0.05	2.72 ± 0.07				
Broken PL	0.21	2.38 ± 0.05	2.1 ± 0.3	$3.4^{+0.3}_{-0.4}$	103^{+12}_{-9}		
Exponential	0.07	2.33 ± 0.05				39 ± 2	
Therm. Compt.[b]	0.11	2.25 ± 0.08				37^{+10}_{-6}	$2.7^{+1.0}_{-0.7}$
Pair Plasma (PP)	0.01	$1.29^{+0.17}_{-0.04}$	$2.37^{+0.2}_{-0.3}$				$2.7^{+1.0}_{-2.7}$
PP with α=1.7	7×10^{-4}	$4.7^{+1.6}_{-1.9}$	1.7^c				> 8

Table 1: OSSE spectral fits of NGC 4151 in the energy range 65 – 800 keV

[a]flux at 100 keV in 10^{-5} photons cm^{-2} s^{-1} keV^{-1}

[b]following Sunyaev & Titarchuk (1980)

[c]fixed parameter

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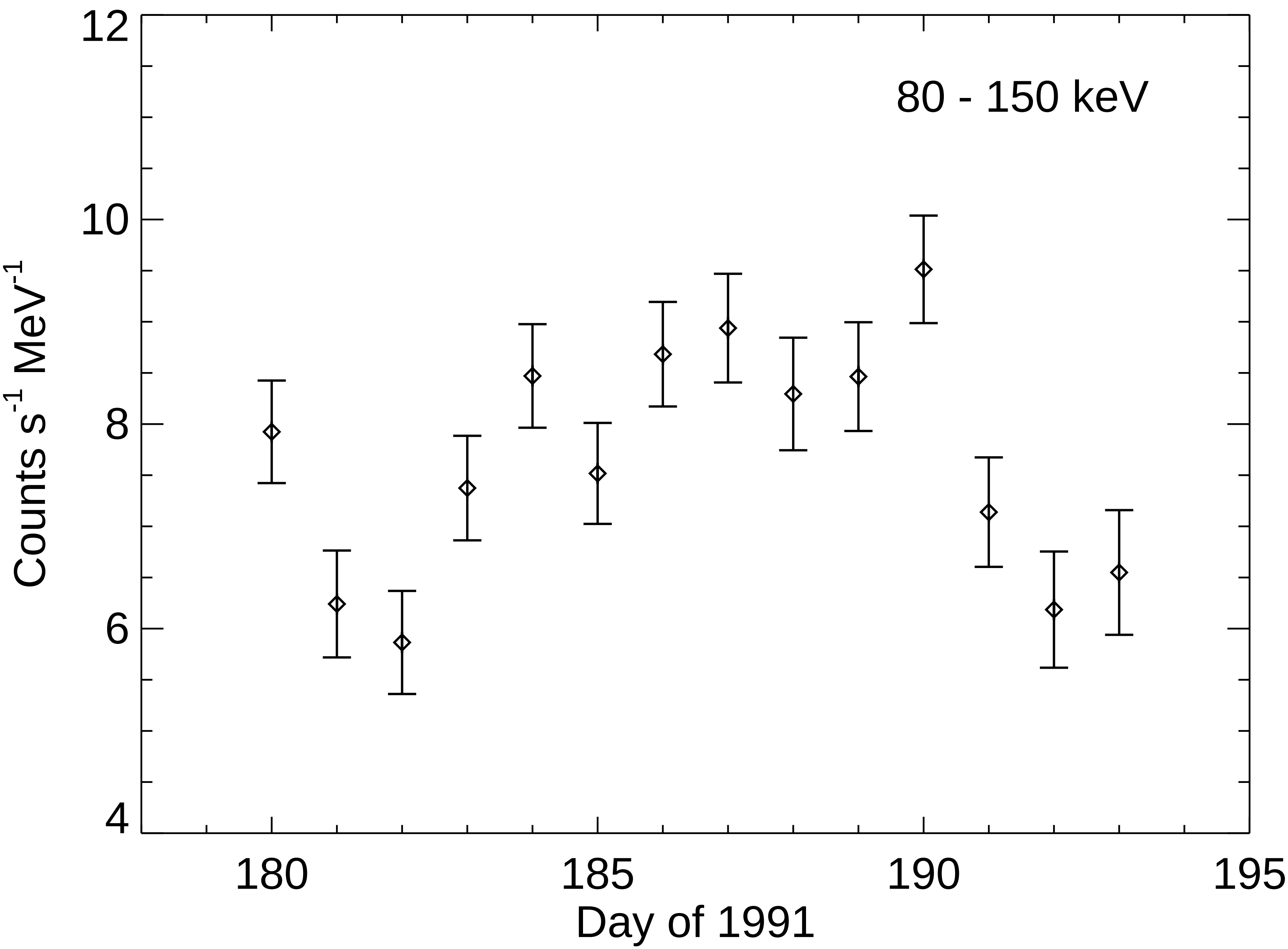
Figure 1: The daily average intensities of NGC 4151 detected by OSSE in the $80 - 150$ keV energy interval.

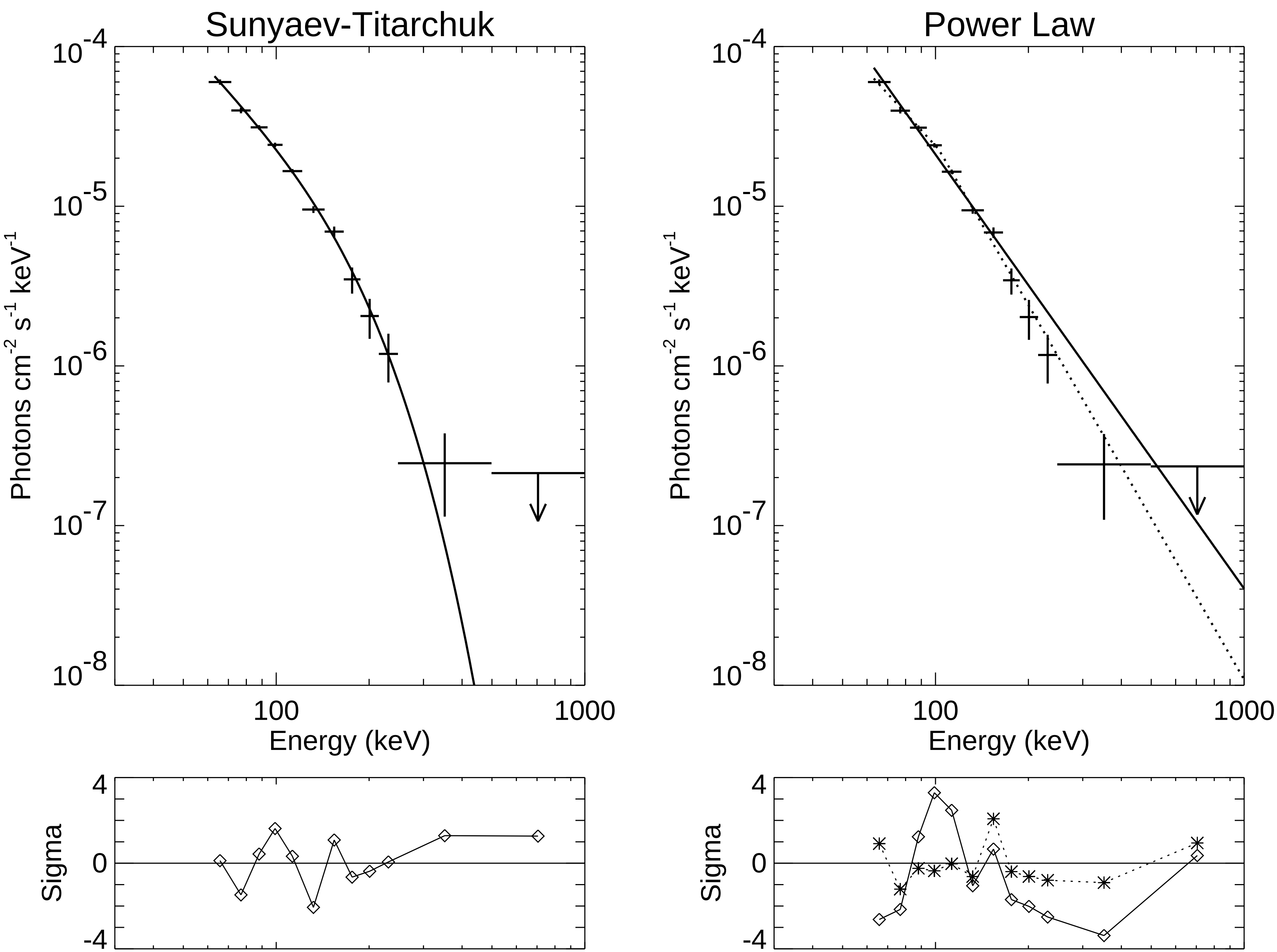
Figure 2: Spectral fits to the OSSE spectrum of NGC 4151. Top left: Sunyaev-Titarchuk Comptonization fit to the photon spectrum. Bottom left: Fit residuals in standard deviations. Right side: Power law fits and residuals. The solid line represents the best fit single power law; the dotted line is the best fit broken power law (see Table 1). Upper limits are plotted at the 2σ confidence level.

Figure 3: The OSSE spectrum in relation to selected previous observations, MISO (Perotti et al. 1990), Ginga/HEXE (Maisack and Yaqoob 1991) and SIGMA (Jourdain et al. 1992). The solid curve is the best fit to OSSE data of a Sunyaev-Titarchuk thermal Comptonization model.

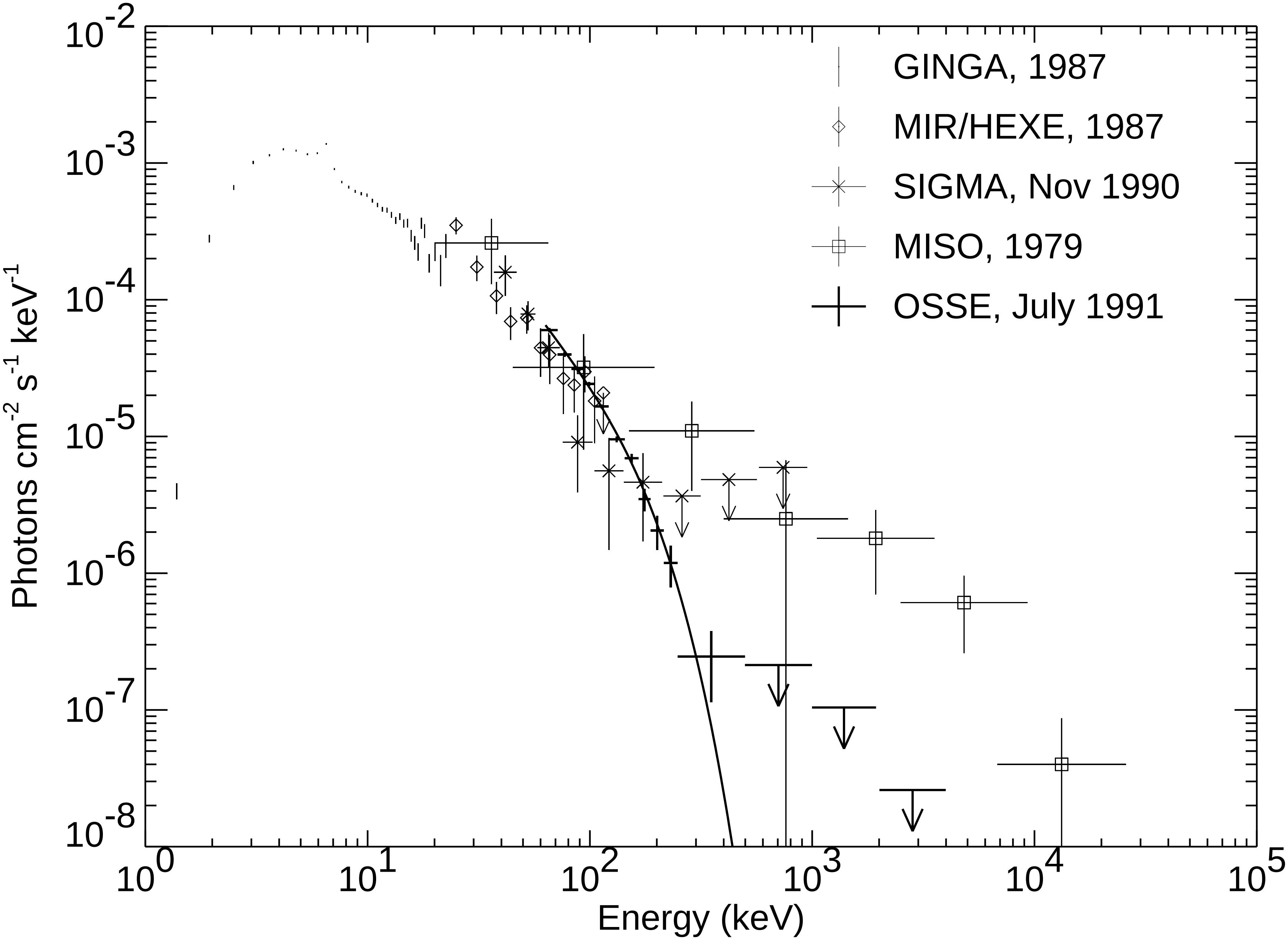
Figure 4: The OSSE spectrum in relation to the nonthermal pair model of Coppi and Zdziarski (1992). The spectrum is plotted as spectral luminosity per logarithmic photon energy interval assuming a distance of 20 Mpc to NGC 4151. The solid line represents the model as applied to the 1990 observation by GRANAT (ART-P and SIGMA) which indicated a typical X-ray spectrum with a break at 50 keV. The dashed line is the model applied to the Ginga/HEXE data observations of 1987 which were consistent with a single power law of index 1.5. No attempt was made to fit their model to the OSSE data.



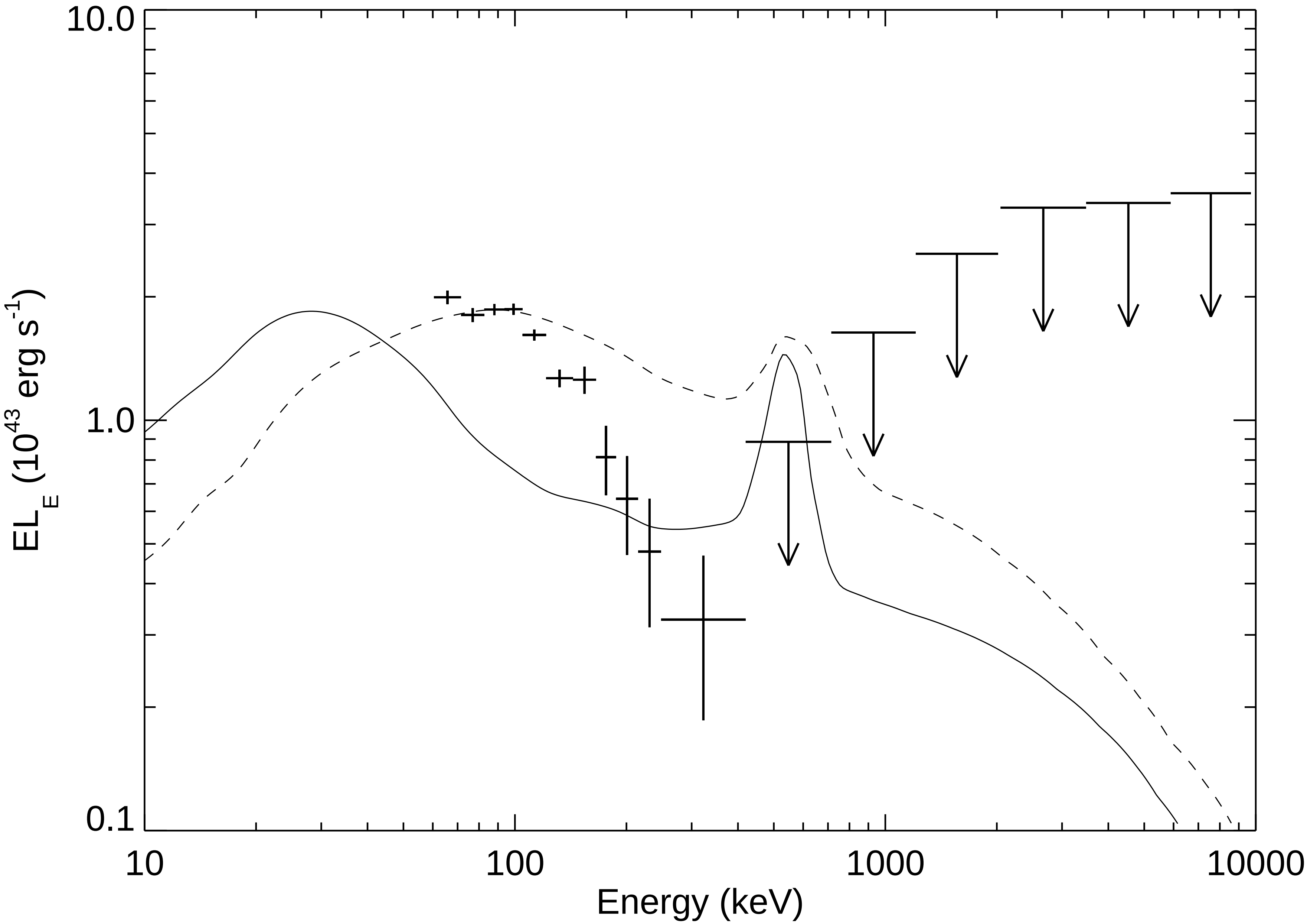
80 - 150 keV
Counts s-1 MeV-1
Day of 1991
4
6
8
10
12
180
185
190
195



Sunyaev-Titarchuk
Power Law
Photons cm^-2 s^-1 keV^-1
10^-4
10^-5
10^-6
10^-7
10^-8
100
1000
Energy (keV)
Sigma
4
0
-4



GINGA, 1987
MIR/HEXE, 1987
SIGMA, Nov 1990
MISO, 1979
OSSE, July 1991
Photons cm-2 s-1 keV-1
Energy (keV)
10-2
10-3
10-4
10-5
10-6
10-7
10-8
100
101
102
103
104
105



10.0
1.0
0.1
10
100
1000
10000
Energy (keV)
EL_E (10^43 erg s^-1)