OSSE OBSERVATIONS OF NGC 4151

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ABSTRACT

We report results of a two-week observation of NGC 4151 with the OSSE instrument. The source had a very soft spectrum which falls off exponentially with an e-folding energy of 39.2±1.5 keV in the energy range 65-800 keV, and had an intensity at 100 keV of $2.33 \pm 0.05 \times 10^{-2}$ photons cm^{-2} sec^{-1} MeV^{-1}. Simple pair cascade models in a compact source, which have been suggested for Seyfert galaxies, cannot explain the steepness and shape of the spectrum above 100 keV. We suggest pair loading and reacceleration as the mechanism responsible for the observed X-ray and gamma-ray spectra and the previously reported lumi.osity - spectral index correlation between $2 - 20$ keV.

INTRODUCTION

NGC 4151, the archetype of Seyfert 1 galaxies, has been the object of various campaigns at all wavelengths. It is also one of the 4 Active Galactic Nuclei (AGN) detected significantly prior to GRO in the energy range 100 keV to 10 MeV[1]. By studying a sample of Seyfert 1 galaxies with HEAO-A4, it was found[2] that Seyfert galaxies have a canonical spectral shape at energies between 20 and 100 keV, described by a power law with photon index $\alpha = 1.7$. Previous observations of NGC 4151 have detected power law spectra with photon indices $\alpha \approx 1.7$, sometimes up to MeV energies[3]. The current observations represent the most sensitive observation of NGC 4151 to date in this energy range, and provide important new information.

OBSERVATIONS AND RESULTS

OSSE observed NGC 4151 from 1991 June 28 to July 12. The total on-source observation time for the sum of four detectors was 8.6×10^5 seconds. A similar amount of time was spent on background observations. A significant

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signal between 65 and 300 keV was observed. The results of spectral fitting 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. The intensity at 100 keV is taken from the exponential fit. It has a value of $2.33^{+0.05}_{-0.05} \times 10^{-2}$ photons cm^{-2} s^{-1} MeV^{-1}, which is comparable to previous observations. A very soft spectrum is observed which cannot be described by a single power law. A spectral fit with this function yields a photon index of 2.72 ± 0.07. The value of χ^2 per degree of freedom is 1.45. The probability for this model is 5×10^{-4}. A broken power law fit gives a photon index of $\alpha_1 = 2.10^{+0.32}_{-0.27}$ below 103^{+12}_{-9} keV and $\alpha_2 = 3.35^{+0.28}_{-0.38}$ above that energy (χ^2_ν=1.09). The spectrum steepens exponentially with an e-folding energy of 39±1.5 keV. A satisfactory fit can also be achieved by a more physical model like thermal Comptonization[4]. This model gives a plasma temperature of 33^{+9}_{-6} keV and optical depth of $2.7^{+1.0}_{-0.6}$ (χ^2_ν=1.15). Figure 1 shows the Sunyaev-Titarchuk spectral fit to the OSSE data.

Table 1: Spectral Fit Summary

Model	χ^2	I[a]	α	α_2	E_{Br}	kT	τ
Power Law	1.45	2.11	2.72				
Broken PL	1.09	2.38	$2.10^{+0.32}_{-0.27}$	$3.35^{+0.28}_{-0.38}$	103^{+12}_{-9}		
exponential	1.19	$2.33^{+0.05}_{-0.05}$				$39^{+1.5}_{-1.5}$	
Comptoniz.	1.15	2.25				37^{+10}_{-6}	$2.7^{+1.0}_{-0.7}$
Pair Plasma	1.30	1.29	2.37				2.7

[a] flux at 100 keV in 10^{-2} photons cm^{-2} s^{-1} MeV^{-1}
[b] fixed parameter

The OSSE spectrum shows NGC 4151 in an extremely soft state with a thermal character which cannot be described by a single power law, contrary to previous, less sensitive observations. A spectrum as steep as the one observed here has been observed only once before: GRANAT recently found a hard spectrum from 3 – 30 keV[5] ($\alpha = 1.44 \pm 0.03$) together with a steeper spectrum from 50-300 keV[6] ($\alpha = 3.1^{+1.1}_{-0.9}$). In contrast, hard, non-thermal power law spectra ($\alpha \approx 1.5$) at energies above 100 keV have been reported for NGC 4151 on several occasions, sometimes extending to energies of several MeV[3]. More observations of NGC 4151 during the mission lifetime of GRO will show whether there are two distinct spectral states and which one is prevalent.

DISCUSSION

Previous observations have shown that the X-ray emission from NGC 4151 follows a luminosity-spectral index correlation in which the spectrum becomes steeper as the source brightens[7]. The spectral indices in the 2-20 keV band vary between 1.3 and 1.7. A model for the gamma-ray emission must also explain this correlation. The most successful models so far include pair cascades[7,8]. In such pair models, the primary X-ray spectrum is generated by Comptonization of soft photons from the "blue bump" by relativistic electrons. The photon density above 511 keV can be so high that electron-positron pair production by photon-photon collisions reprocesses a significant portion of the primary radiation. The effect of pair cascades is a steepening of the X-ray spectrum with increasing compactness. It reflects the depletion of the gamma ray spectrum above 511 keV by pair production and hence the spectral distribution of pairs, which by their emission contribute increasingly to the X-ray spectrum. A measure for the importance of this effect is the compactness parameter l defined as[9]

$$l = \frac{L_X \sigma_T}{R m_e c^3} \tag{1}$$

where L_X is the X-ray luminosity, σ_T the Thomson cross section, R the source radius, m_e the electron rest mass and c the speed of light. The seed photon compactness l_s and the injected electron compactness l_e are defined accordingly. For NGC 4151, l_e is estimated to be in the range $1 - 10^{10}$.

The "canonical" index of $\alpha = 1.7$ is only compatible with the OSSE data up to an energy of 100 keV. Above 100 keV, the spectral slope derived from the broken power law fit is $\alpha = 3.35^{+0.28}_{-0.38}$. Such a steep high-energy spectrum cannot be explained by simple pair cascade models, in which a steepening due to Compton downscattering in a plasma of cooled pairs produces a spectrum which steepens by $\Delta\alpha = 1$ above an energy of $511/\tau^2$ keV, where τ is the optical depth of the pair plasma[11]. Fitting this spectral shape gives an unacceptable chi-square ($\chi^2_\nu = 1.30$ for 130 degrees of freedom).

It has been suggested[12] that a modification of pair models can reproduce a luminosity-spectral index correlation together with a steep spectrum as observed by OSSE. In this model, a fraction of the injected particles (electrons and positrons, collectively referred to as electrons) are continuously reaccelerated to high energies after they have radiated their primary energy. These reaccelerated particles then form a substantial part of the relativistic particle population. At the same time this reacceleration mechanism can only supply a limited amount of acceleration power. The number of particles eligible for acceleration therefore limits the average energy available per particle, i.e., the mean γ factor of accelerated electrons decreases when the number of accelerated particles increases once the accelerator operates at its maximum power output. Done, Ghisellini and Fabian[12] found that for a source in which reacceleration occurs the maximum γ factor can decrease to several tens (assuming γ factors of several 1000 for freshly injected particles) as the electron compactness increases to values of l_e = 10-100, if two conditions are met: The source must be photon starved and escape of particles from the source region is possible. Photon starvation occurs when there are more energetic particles than target photons, so that second-order Comptonization becomes important. This can result in spectra with a harder index than $\alpha = 1.5$. In a photon-starved source, the pair yield is higher than in the non-starved case. It thus provides more particles to load the accelerator and enhances the reduction in γ. Escape of particles from the source region is required to explain the behavior of NGC 4151. Escape suppresses the effect of loading at low compactness since it removes particles from the accelerator and makes injection more important, i.e., with escape, γ_{max} is larger for small l_e than in the purely photon-starved case. The low γ factors can explain why the spectrum does not extend to energies above 511 keV, since a first-order Comptonized spectrum extends[13] to energies of $\frac{4}{3}\gamma^2\epsilon$ where ϵ is the energy of the soft target photons in units of the electron rest mass energy. Assuming $\epsilon = 10^{-4}$ for the energy of the target photons (assuming a "blue bump" origin) and inserting the Sunyaev-Comptonization fit temperature of the OSSE data of 30-40 keV gives a maximum γ factor of $\approx$ 25-30. This suggests that l_e during the OSSE observation is on the order of several tens.

A source in which reacceleration occurs under the above assumptions therefore provides the observed index-luminosity correlation in the following way: at low l_e, the spectrum is hard ($\alpha < 1.5$) and may extend beyond 511 keV, while at the same time pair reprocessing is unimportant because of the low compactness. When the compactness l_e (i.e., number of injected particles) increases, the average electron energy decreases as long as l_e is on the order of several tens (see Fig.2b in Ref. 12). With more electrons being accelerated to lower energies, their energy spectrum becomes progressively softer as the importance of loading increases. Above a compactness of 100, injection dominates reacceleration as the main supplying mechanism of high-energy particles and the effect of loading diminshes.

SUMMARY

OSSE has observed NGC 4151 to have a spectrum with a thermal character which steepens exponentially with an e-folding energy of 39$\pm$2 keV. Simple pair models cannot explain the observed behavior. An acceleration process which acts on both freshly injected and cooled particles and has a limited power output can explain the observations if the source is photon starved and if escape of particles from the source region is possible. The soft spectrum in this model reflects the lower particle energy spectrum, which is caused by the loading of the acceleration mechanism. 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 even dominant in this class of source.

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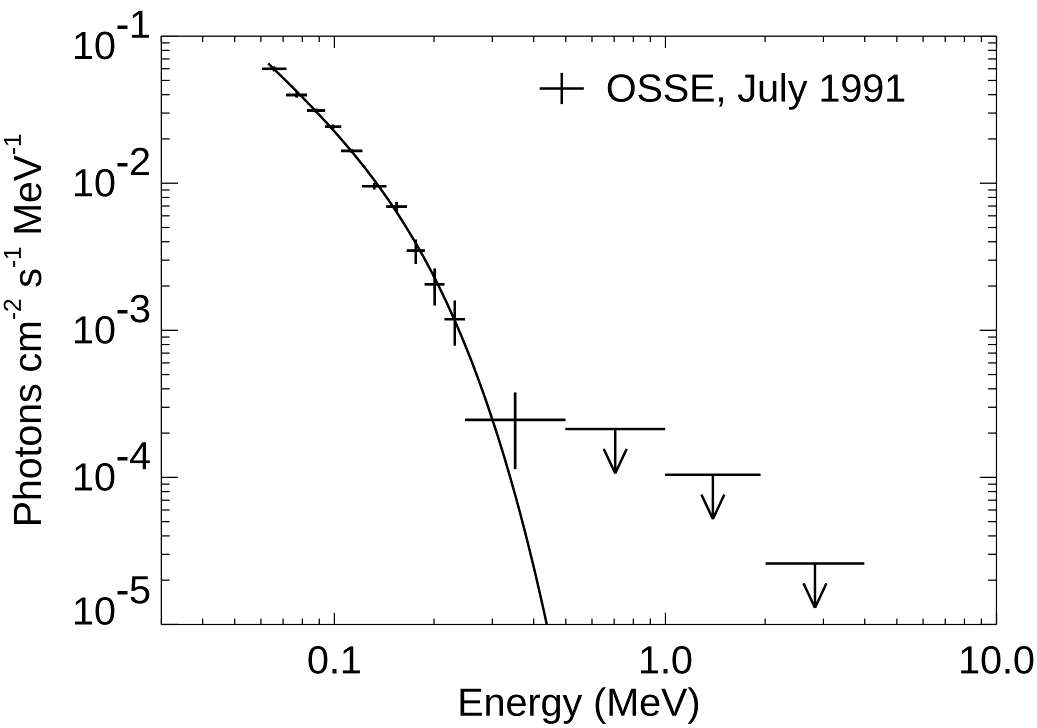

Figure 1: OSSE spectrum with thermal Comptonisation fit

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