THE ASTROPHYSICAL JOURNAL, 433:L33–L36, 1994 September 20

HARD X-RAYS FROM NGC 4151: A THERMAL ORIGIN?

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Received 1994 April 19; accepted 1994 July 7

ABSTRACT

We present a model for explaining the recent combined X-ray and low-energy gamma-ray observations of the Seyfert galaxy NGC 4151. According to this model, soft photons become Comptonized in a hot spot producing simultaneously the low-energy power law as observed by *Ginga* and the high-energy cutoff observed by *OSSE*. Implementing recently developed theoretical calculations toward a generalized theory of Comptonization, we were able to find fits to the observations using only two parameters which characterize the physical quantities of the emission region: the plasma cloud optical depth and its temperature. We find that there is no need for additional nonthermal, reflection, or higher temperature thermal components to fit the aforementioned *OSSE* and *Ginga* observations. We derive in addition the size of the photon region and the temperature of the upscattered soft photons. We should emphasize, also, that any attempt at fitting only the high-energy parts of the spectrum (photon energies >60 keV) by the Sunyaev & Titarchuk (1980) nonrelativistic Comptonization model leads to an underestimate of the Comptonization parameter y (or, equivalently, to an overestimation of the X-ray power-law spectral slope) and leads, as a result, to incorrect proportions between the low-energy and high-energy parts of the spectrum.

Subject headings: galaxies: Seyfert — plasmas — radiation mechanisms: thermal — radiative transfer — relativity

1. INTRODUCTION

NGC 4151 is the nearest Seyfert galaxy (20 Mpc for $H_0 = 50$ km s^{-1} Mpc^{-1}). Its proximity has made it one of the most studied AGNs with observations covering the whole electromagnetic spectrum. Specifically, in the high-energy X-ray regime, some pre-*GRO* balloon observations have detected the source up to MeV energies (for a compilation of these observations, see Perotti et al. 1990). However, the recent SIGMA (Jourdain et al. 1993) and *OSSE* (Maisack et al. 1993) observations have both detected a spectral break below 100 keV. This might imply either that NGC 4151 sometimes switches onto a high gamma-ray state or that the earlier observations were wrong. On the other hand, in the lower energy X-ray regime the situation is clearer. NGC 4151 is well established as a source of 2–10 keV X-rays (Holt et al. 1980). Its luminosity is rather low, varying between 10^{42} and 10^{43} ergs s^{-1}, while the power-law energy index varies in the range 0.5 ± 0.2 (Yaqoob et al. 1993). Furthermore, an iron Kα line has persistently been observed (Perola et al. 1986; Yaqoob, Warwick, & Pounds 1989) with features that strongly indicate that it is formed in cold material (Matsuoka et al. 1986).

Many models have been investigated so far to explain the origin and nature of the X-rays from NGC 4151. These include, among others, nonthermal pair plasma models (Coppi & Zdziarski 1992), reflection (Maisack & Yaqoob 1991), and thermal Comptonization (Maisack et al. 1993). The unprecedented quality, however, of the recent *OSSE* observations was bound to constrain severely or rule out altogether many of these models. More specifically, the upper limit which *OSSE* has put on the annihilation line in the spectrum of NGC 4151 seem to exclude for the time being the nonthermal plasma models. Zdziarski, Lightman, & Maclolec-Niedzwieski (1993) have recently proposed a hybrid model where only a small part of the acceleration efficiency is used in accelerating nonthermal particles. On the other hand, purely thermal models seem adequate to explain NGC 4151 (Maisack et al. 1993).

In the present *Letter* we attempt to explain the high-energy spectrum of NGC 4151 in terms of these thermal Comptonization models. The motivation for this work was given not only by the aforementioned observations but also from recent theoretical efforts in generalizing the theory of Comptonization, as presented by Sunyaev & Titarchuk (1980, 1985; hereafter ST80 and ST85, respectively). More precisely, it is a well-known fact that for high electron temperatures ($T_e > 30$ keV) the ST formula deviates from the exact results by amounts which are greater than the observational uncertainties, as the relativistic corrections to the Klein-Nishina cross section and the scattering kernel cannot be ignored. To deal with this situation, one of us (Titarchuk 1994, hereafter T94) has generalized the Comptonization theory to include the necessary relativistic effects in order to study their influence on the resulting spectra. Because the effects due to these corrections not only affect the high-energy (exponential cutoff) part of the Comptonized spectrum, but also the power law at lower energies, it is important that these improved formulae should be used when fitting data extending over a broad range of frequencies. To date the only published results of this kind are the combined *Ginga* (Yaqoob et al. 1993) and *OSSE* (Maisack et al. 1993) data sets for NGC 4151. Indeed, we find that the combined set of observations cannot be fitted with a single Sunyaev-Titarchuk spectrum of a given temperature and optical depth. In general the *Ginga* data are fitted by a power-law with a spectral slope of 0.5 ± 0.2 but the spectral index derived from the best-fit parameters for the *OSSE* data give rise to a spectral slope of value $1. \pm 0.2$. It is impossible to reconcile this difference in terms of the simple nonrelativistic Comptonization model of ST80. However, using the formulae derived from the generalized thermal Comptonization we find that *by fitting only OSSE data we produce automatically the*

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power-law energy part with the appropriate normalization which corresponds to the Ginga points (see Fig. 2).

The present *Letter* is structured as follows. In § 2 we give a brief description of the generalized theory of Comptonization putting emphasis on the derived analytic formula; in § 3 we give a plausible physical picture which could account for the production of the radiation; in § 4 we present fits to the existing data; and we conclude in § 5 with a brief discussion.

2. ANALYTICAL SOLUTION

A detailed treatment of the generalized theory of Comptonization is given elsewhere (T94). Here we repeat only what are its most important points, for our present purposes.

The problem of the spectral and angular distribution of photons undergoing scatterings in a hot plasma cloud has been analyzed by ST80 and ST85. The solution of this problem is closely connected with the distribution law for the number of scatterings. As was shown in ST80, the exponential tail $\exp(-\beta u)$ of this distribution is a typical feature of photons escaping from a confined region of space. Here u is the number of scatterings, while β is related to the mean number of scatterings $\bar{u}$ in the plasma cloud characterized by some optical depth τ_0. For the parameter β we derive the following expressions which are a combination of its asymptotic forms for small and large optical depths:

$$\beta = \begin{cases} \dfrac{\pi^2}{12(\tau_0+2/3)^2}(1-e^{-1.35\tau_0}) + 0.45e^{-3.7\tau_0}\ln\dfrac{10}{3\tau_0} & \text{for disks}, \\ \dfrac{\pi^2}{3(\tau_0+2/3)^2}(1-e^{-0.7\tau_0}) + e^{-1.4\tau_0}\ln\dfrac{4}{3\tau_0} & \text{for spheres}. \end{cases} \quad (1)$$

Solving the radiative transfer equation (see T94) in the case of monoenergetic primary sources emitting at a low frequency ν_0, we obtain the flux emerging from the plasma cloud by means of the Whittaker functions

$$F_\nu(x, x_0) = \alpha_0(\alpha_0+3)\frac{e^{-x}}{x_0}\left(\frac{x}{x_0}\right)^{-\alpha_0}\frac{\int_0^\infty t^{\alpha-1}(x+t)^{\alpha+3}e^{-t}dt}{\Gamma(2\alpha+4)} \quad \text{when} \quad x^* > x \geq x_0 . \quad (2)$$

Here $x = h\nu/kT_e$ is the dimensionless photon energy; $\alpha_0 = (9/4+\gamma_0)^{1/2} - 3/2$ is the power-law slope of the low-energy part; $\Theta = kT_e/m_e c^2$ is the dimensionless plasma temperature; $\gamma_0 = \beta/\Theta[1+f_0(\Theta)]$ is the Comptonization parameter, while $x_* = 0.5 + \gamma_0$ is the boundary of the low-energy part. Furthermore we define the functions $f_0(\Theta) = 2.5\Theta + 1.875\Theta^2(1-\Theta)$, $\alpha(x) = [9/4 + \gamma(x)]^{1/2} - 3/2$; $\gamma(x) = \gamma_0 Q_\nu P_\nu$. The function $Q_\nu = 1 + 2.8(1-1.1\Theta)z - 0.44z^2$ is valid with an accuracy of better than 2% in the range $h\nu < 1$ MeV (Grebenev & Sunyaev 1988; T94). The function $P_\nu(x) = (1 + 4.6\Theta x + 1.1\Theta^2 x^2)$ derived by Cooper (1971) (also see Prasad et al. 1988) has accuracy of better than 1% in the range $h\nu < 1$ MeV. Furthermore, the values of β are obtained from equation (1).

The spectrum $F(x, x_0)$ for $x > x_*$ is given by the formula

$$F(x, x_0) \simeq c_0 x^{3-b_1} e^{-x(1+b_0)} , \quad (3)$$

where $b_0 = \{[1 + 54.2\Theta^2 p(\Theta)\gamma_0]^{1/2} - 1\}/2$, $b_1 = [4b_0 + 7.4\Theta q(\Theta)\gamma_0]/(1+2b_0)$, $p(\Theta) = 1 - 1.05\Theta$, $q(\Theta) = 1 - 0.42\Theta$, and the coefficient c_0 is determined by the continuity condition between the two parts of the spectrum (eqs. [2] and [3]) at $x \simeq x_*$.

It is worth noting the difference between the nonrelativistic shape and the relativistic one. Instead of the power law with the spectral slope $\alpha_{nr} = (9/4 + \beta/\Theta)^{1/2} - 3/2$ which characterizes the nonrelativistic case we have the flatter power law with the spectral slope α_0 (see eq. [2]) and instead of the Wien tail $x^2 e^{-x}$ which represents the hard tail in the nonrelativistic case, in the relativistic case we have the steeper tail $x^{3-\nu b_1} e^{-x(1+b_0)}$. As is shown in T94, the new analytical formula is much more precise than the nonrelativistic approximation of ST80.

3. THE PHYSICAL MODEL

Trying to develop a physical model that could account for the production of hard X-rays, we will adopt here the "sandwich model" proposed by various authors (see, e.g., Ionson & Kuperus 1984; Sunyaev & Titarchuk 1989; Haardt & Maraschi 1991). This model assumes the presence of a hot region in the vicinity of relatively cold material. The hot region itself can be produced by Coulomb collisions between energetic protons and electrons; the details, however, of its production are irrelevant to our present treatment. The hard photons coming from the hot region heat the cold material mainly due to photoelectric absorption and to the recoil effect, with the latter being more dominant for harder radiation. As a result, the heated part of the cold region will emit soft radiation, and the whole picture can then be solved self-consistently as it is this soft radiation that gets Comptonized in the hot region producing the hard radiation (Sunyaev & Titarchuk 1989). It is worthwhile noting that the shape of the emergent spectrum is independent of the energy of the soft photons and it is determined by the plasma temperature kT_e and the optical depth τ_0. In other words, the characteristic photon energy of the spectrum (weighted over the spectrum) depends on the plasma temperature and the optical depth only. However, the albedo of the cold material is determined by this averaged photon energy, and in turn it controls the fraction of the hard radiation which is deposited there, and it is converted into the low-frequency radiation. But the same ratio of the hard photon flux to the soft photon flux can be found by calculating the enhancement factor due to Comptonization in the plasma cloud with the given plasma temperature and optical depth. Thus the soft photon energy could be found by equating those two ratios. A more detailed picture of this feedback mechanism will be presented elsewhere (Titarchuk 1994b), while for our present purpose, it is sufficient to give a brief description of the main conclusions.

Let L and L_0 be the luminosities of the hard and soft radiation, respectively. Then, assuming that about half of the hard radiation irradiates the cold matter, the luminosities are related by the expression

$$L_0 = \frac{(1-A)L}{2} , \quad (4)$$

where A is the albedo of the cold material. The expression for the monochromatic albedo, taking into account only the recoil effect, is given by Titarchuk (1987) as

$$1 - A_\nu = \sqrt{\frac{\pi}{3}\frac{h\nu}{m_e c^2}} . \quad (5)$$

Thus for the flux-averaged albedo we can write

$$1 - A = \frac{\int_0^\infty (1-A_\nu)F_\nu d\nu}{\int_0^\infty F_\nu d\nu} \simeq \sqrt{\frac{\pi}{3}\frac{kT_e}{m_e c^2}}\frac{\Gamma(\delta+1.5)}{d^{0.5}\Gamma(\delta+1)} . \quad (6)$$

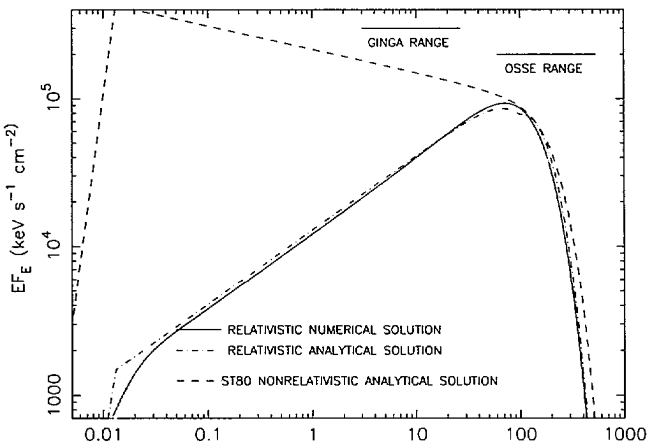

FIG. 1.—Comparison of the ST80 nonrelativistic model with the relativistic model of T94 (both analytical and numerical). The parameters were chosen in such a way as to give the best fit to the *OSSE* data and are given in the text.

We have assumed, in accordance with our earlier discussion, that this flux is given by the hard tail formulae (3) ($F_\nu \simeq c_0 x^\delta e^{-xd}$) and thus here $d = 1 + b_0$ and $\delta = 3 - b_0$. In addition to equation. (4), L and L_0 ($L_0 = 1$ in eq. [2] and [3]) are related by the expression for the enhancement factor due to the upscattering of photons

$$\frac{L}{L_0} = \int_0^\infty F_\nu\, dx \simeq c_0 \frac{\Gamma(\delta + 1)}{d^{\delta+1}} . \quad (7)$$

As we have mentioned before, the coefficient c_0 is determined by the continuity condition between the two parts of the spectrum (eqs. [2] and [3]) at $x \simeq x_*$; thus

$$c_0 \simeq \frac{\alpha_0(\alpha_0 + 3)e^{-b_0 x_*}}{(2\alpha_0 + 3)x_*^{\alpha_0+\delta}}\, x_0^{\alpha_0 - 1} . \quad (8)$$

Therefore, one can eliminate L and L_0 from equations (4) and (7) and solve at once for the frequency of soft radiation

$$x_0 = \left[\frac{1}{2}\sqrt{\frac{\pi k T_e}{3 m_e c^2}}\, \frac{e^{-b_0 x_*}\,\Gamma(3/2 + \delta)\alpha_0(\alpha_0 + 3)}{x_*^{\alpha_0+\delta} d^{3/2+\delta}(2\alpha_0 + 3)}\right]^{1/(1-\alpha_0)} . \quad (9)$$

Thus, by knowing the parameter β and the temperature kT_e one can calculate at once the energy of the soft photons. Equation (9) holds provided that the energy deposition is due to the recoil effect, while it assumes that $x_0 \ll 1$ and $\alpha_0 < 1$.

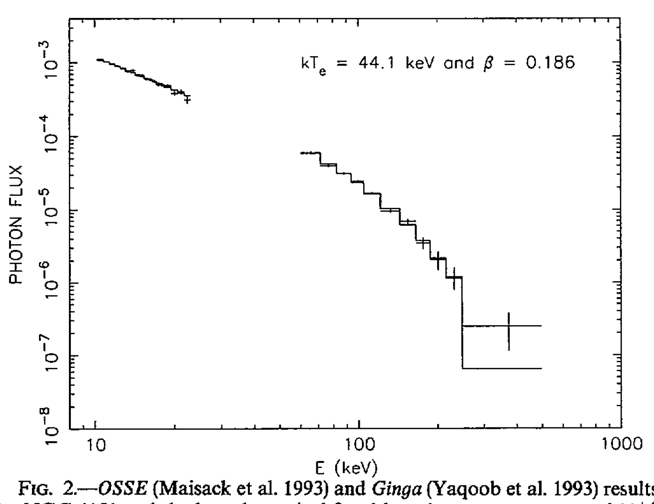

FIG. 2.—*OSSE* (Maisack et al. 1993) and *Ginga* (Yaqoob et al. 1993) results for NGC 4151 and the best theoretical fit with a plasma temperature of 44^{+4}_{-4} keV and $\beta = 0.186^{+0.028}_{-0.023}$ or with the appropriate Thomson optical depth are $1.25^{+0.16}_{-0.18}$ in disk geometry and $3.2^{+0.3}_{-0.37}$ in spherical geometry.

4. FITS TO THE OBSERVATIONS

In this section we apply the generalized theory of Comptonization to the recent *OSSE* (Maisack et al. 1993) and *Ginga* (Yaqoob et al. 1993) observations of NGC 4151. Figure 1 shows three curves in EF_ν versus E diagram. The first one (*dashed line*) represents the ST80 nonrelativistic model with a plasma temperature of 34 keV and a β-parameter of 0.32 (corresponding to a Thomson optical depth of 0.71 for a plane geometry and of 2 for a spherical geometry). The parameters above give the best fit to the *OSSE* observations of NGC 4151 when the nonrelativistic model is used (Maiseck et al. 1993; L. Titarchuk & A. Mastichiadis, independent calculations). The second curve represents the fit to the data using the generalized formulae (2) and (3) with a plasma temperature of 44.1 keV and a β-parameter of 0.186 (corresponding to a Thomson optical depth of 1.13 for a plane geometry and of 3.2 for a spherical geometry). Finally the third curve (*full line*) represents the fit to the data using the exact numerical solution of the photon transfer equation (T94). The parameters used here are the same as the ones for the second curve. First, we note that there is an excellent agreement between the exact numerical solution of the transfer equation and its approximate analytical solution as is given by equations (2) and (3). Second, we note that, over the *OSSE* energy range, both the nonrelativistic and the relativistic model give rather similar fits; however, they do produce completely different power laws for the low-frequency part of the spectrum (the nonrelativistic power law has a spectral slope of 1.1, while the relativistic one has a slope of 0.5). Therefore, the ratio between the two models over the *Ginga* energy range is about one order of magnitude.

Figure 2 shows the *OSSE* (Maisack et al. 1993) and the *Ginga* (Yaqoob et al. 1993) results in terms of the photon flux versus energy and the best theoretical fit given by the relativistic model with a plasma temperature of 44^{+5}_{-3} keV and $\beta = 0.186^{+0.031}_{-0.022}$ (χ^2 probability = 0.1). The corresponding Thomson optical depths are $1.25^{+0.16}_{-0.18}$ for disk geometry and $3.2^{+0.3}_{-0.37}$ for spherical geometry. The best fit with $kT_e = 44.1$ keV and $\beta = 0.186$ gives $\chi^2 = 33.03$ for 29 points. The absorber column density was kept fixed at the best-fit value given by Yaqoob et al. (1993), namely $N_h = 9.8 \times 10^{22}$ cm^{-2}. Assuming an X-ray luminosity equal to 10^{43} ergs s^{-1} and using equations (9), (4), and (6) with the best-fit Comptonization parameters, $\beta = 0.186$ and the temperature $kT_e = 44.1$ keV (the relevant parameters α_0, b_0, b_1, d, δ are functions of β and kT_e and are found to be 0.5, 0.14, 1.28, 1.72, respectively), we produce the appropriate values of the photon blackbody temperature and the emission surface size: $kT_0 = 4.9^{+0.7}_{-1.9}$ eV ($h\nu_0 = 13^{+2}_{-5}$ eV) and $R = 4.8^{+4.4}_{-2} \times 10^{13}$ cm. The appropriate errors in the determination of the low-frequency power spectral slope are even smaller: $\alpha_0 = 0.5^{+0.008}_{-0.02}$.

5. SUMMARY

In this *Letter* we have presented a fit to the recent NGC 4151 *OSSE* observations based on the generalized Comptonization theory. We find that even if the plasma temperatures are one order of magnitude below the electron rest mass, it is necessary to take into account relativistic effects. As expected, the inclusion of the relativistic corrections changes the shape of the Comptonization spectrum: it lowers, on one hand, the power-law spectral slope when the plasma temperature increases (e.g., Prasad et al. 1988) but causes the hard tail (>60 keV) to be steeper (eq. [3]) than the Wien tail which characterizes the nonrelativistic case. This happens because as relativistic effects become dominant, the Compton scattering loses its effectiveness and photons mainly escape in the forward direction changing their energy only slightly. In other words the photons cannot attain the high-energy barrier $3kT_e$ before escaping the plasma cloud. For plasma temperatures ~40–50 keV and for optical depths ~1, values which are typical for black hole candidate sources, the peak of the spectrum in the EF_ν versus E diagram occurs at $E \sim 2kT_e$. Only the nonrelativistic models, ST80 with a γ_0 of around 4 (or the low-frequency slopes of around 1) mimic such hard tail behavior. *Any attempt of fitting the high-energy parts of the spectrum by the nonrelativistic model leads to an underestimate of the Comptonization parameter* $y \propto 1/\gamma_0$ *(or to an overestimation of the low-frequency power-law spectral slope) and as a result to incorrect proportionality between the low-energy and high-energy parts of the spectrum (see Fig. 1).*

While the relativistic fit of the *OSSE* data alone is about as good as the fit one can derive from a straight application of the usual Sunyaev-Titarchuk formula (Maisack et al. 1993; L. Titarchuk & A. Mastichiadis, independent calculations), *we find that only with the new formulae given by equations (2) and (3) one can fit the Ginga data points in the lower energies (10–20* keV) *and, simultaneously, the OSSE data points in the higher energies (60–500* keV). *In order to do so we use only two parameters which characterize the physical properties of the emission region, namely the plasma cloud optical depth and its corresponding temperature. By fitting on the OSSE data we produce automatically the power-law energy part with the appropriate normalization which corresponds to the Ginga points (see Fig. 2).*

Our conclusions, requiring further confirmation, point in the direction that the X-rays from Seyfert galaxies might be due to Comptonization of soft radiation by thermal electrons. This is further strengthened from the fact that *OSSE* has not observed any annihilation lines from Seyfert galaxies—these annihilation lines are a signature for a certain class of nonthermal models; see, for example, Lightman & Zdziarski (1987). While some other nonthermal models (Mastichiadis & Kirk 1994) might present the observed features as well (i.e., breaks around some tens of keV and weak annihilation lines), it remains to be seen how well they can fit the observations.

We would like to acknowledge support from a NRC grant. We also acknowledge extensive valuable discussions with D. Kazanas and also acknowledge N. Johnson and T, Yaqoob for the data sources. In particular the authors appreciate the anonymous referee's very sharp critique and very useful advice which helped to clarify the main message of this *Letter*.

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