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Hard X-rays from NGC4151: A Thermal Origin?

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ABSTRACT

We present a model for explaining the recent X-ray observations of the Seyfert galaxy NGC 4151. According to this model soft photons get Comptonized in a hot spot producing simultaneously the low energy (2-20 keV) power-law and the high energy (>30 keV) cutoff. Using recently developed theoretical calculations towards a generalized theory of Comptonization, we were able to find fits to the observations and derive in addition useful physical quantities as the size of the soft photon region and the temperature of the upscattered soft photons.

Subject headings: radiation mechanism: globular – X-rays: NGC 4151 – galaxies

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. Especially 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 and OSSE observations have both detected a spectral break below 100 keV. This might imply that NGC 4151 sometimes switches onto a high gamma-ray state or that, alternatively, the earlier observations were wrong. On the other hand, in the lower energy X-ray regime the situation is more clear. 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} to 10^{43} erg/sec, while the photon energy spectrum has a value of 0.5 ± 0.2 (Yaqoob et al. 1993). Furthermore, an iron K_α line has persistently been observed (Perola et. al 1986, Yaqoob, Warwick and Pounds 1989) with features that strongly indicate that it is formed in cold material (Matsuoka et al. 1986).

Many models have been proposed so far to explain the origin and nature of the X-rays from NGC 4151. These include, among others, non-thermal 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 non-thermal plasma models. Zdziarski

et al. (1993) have recently proposed an hybrid model where only a small part of the acceleration efficiency is used in accelerating non-thermal particles. On the other hand, purely thermal models seem adequate to explain NGC 4151 (Maisack et al 1993). In the present paper 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 this was presented by Sunyaev and Titarchuk (1980, 1985 – from now on ST80 and ST85). More precisely, it is a well known fact that for high temperatures the ST formula breaks down as relativistic corrections to the Klein-Nishina cross section and the scattering kernel cannot be ignored. To deal with this situation, one of us (LT, submitted to *ApJ*) has generalized the Comptonization theory to include the necessary relativistic effects. Using the formulas derived from this ‘generalized’ thermal Comptonization we have attempted to fit (i) the hard (OSSE) X-ray data and (ii) both soft (GINGA) and hard (OSSE) X-ray data. However, we should warn the reader that in the latter case the observations are not contemporaneous but they were performed with a time difference of one month. Whether the source has changed state in this time is largely unknown.

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

2. Analytical solution

A detailed treatment of the generalized theory of Comptonization is given elsewhere (Titarchuk 1994 - from now on T94). Here we repeat only its most important, for our present purposes, points.

The basic approach is in general similar to the approach taken in ST80 and ST85 with the following modifications. In order to generalize the photon diffusion approach, which can be applied only to the cases where the optical depth of the scattering cloud τ_0 is much greater than unity, to the case of an arbitrary optical depth, we have replaced the diffusion operator $L_r^{(d)}$ with the radiative transfer operator L_r (see, e.g., Chandrasekhar 1960). Also, in order to include relativistic effects, the transport cross-section of scattering by electrons can be approximated by $\sigma_{tr} \simeq \sigma_T \varphi(z) = \sigma_T (1 + 2.8zf(\Theta) - 0.44z^2)^{-1}$ where σ_T is Thomson cross section, $z = \frac{h\nu}{m_e c^2}$ is the dimensionless photon energy, $f(\Theta) = 1 - 1.1\Theta$ is

the temperature factor and $\Theta = \frac{kT_e}{m_e c^2}$ is the dimensionless plasma temperature.

The function $\varphi(z)$ is approximated by Grebenev & Sunyaev (1988) and T94 analytically with an accuracy of better than 2% in the range $h\nu < 1$ MeV. Finally the time evolution of the photon energy is determined by the Doppler and recoil effects as derived by Prasad et al. (1988) and it may be approximated with an accuracy 1% in the range $kT_e < 100$ keV by the relation (see Cooper 1971) $\eta(z, \Theta) = z^4(1 + 4.6z + 1.1z^2)^{-1}(1 + f_0(\Theta))$, where $f_0(\Theta) = 2.5\Theta + 1.875\Theta^2(1 - \Theta)$ and As it was shown in ST80 the asymptotic of the photon distribution over the escape time is described by the exponential law $\exp(-\beta u)$ where u is the number of scatterings. In the diffusion approximation the parameter β given by the relation $\beta = \lambda_1^2/3$ represents the first eigenvalue of the differential operator $L_r^{(d)}$ with the appropriate boundary conditions. ST80 have derived analytically the values of β for the two limiting cases $\tau_0 \gg 1$ and $\tau_0 \ll 1$ for disk and spherical geometries. Here we use the following semianalytic relations for β , which include both asymptotics for small and large optical depths,

$$\beta = \frac{\pi^2}{12(\tau_0 + 2/3)^2} (1 - e^{-1.35\tau_0}) + 0.45e^{-3.7\tau_0} \ln \frac{10}{3\tau_0}, \quad \text{disk} \quad (1a)$$

and

$$\beta = \frac{\pi^2}{3(\tau_0 + 2/3)^2} (1 - e^{-0.7\tau_0}) + e^{-1.4\tau_0} \ln \frac{4}{3\tau_0}. \quad \text{sphere} \quad (1b)$$

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

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

Here $x = h\nu/kT_e$, $\alpha(x) = \sqrt{9/4 + \gamma(x)} - 3/2$, $x_* = 0.5 + \gamma_0$, $\gamma = \frac{\beta z^4}{\Theta \eta \varphi}$, $\alpha_0 = \sqrt{9/4 + \gamma_0} - 3/2$ and $\gamma_0 = \frac{\beta}{\Theta(1+f_0(\Theta))}$. Furthermore the values of β are obtained from Eqns (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 $b_0 = (\sqrt{1 + 54.2\Theta^2 q(\Theta)\gamma_0} - 1)/2$, $b_1 = (4b_0 + 7.4\Theta q(\Theta)\gamma_0)/(1 + 2b_0)$, $q(\Theta) = 1 - 1.05\Theta$ and the coefficient c_0 is determined by the continuity condition between the two parts of the spectrum (Eqns 2 and 3) at $x \simeq x_*$. It is worth to remark the difference between the nonrelativistic hard tail and the relativistic one. Instead of the Wien tail $x^3 e^{-x}$ which

characterizes the nonrelativistic case, in the relativistic case we have the steeper tail $x^{3-b_1} e^{-x(1+b_0)}$. As it is shown in T94 the new analytical formula works much better 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’ first proposed by Sunyaev and Titarchuk (1989) (see also Haardt and 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 (see, for example, Guessoum and Kazanas 1990); the details, however, of its production are irrelevant for our present treatment. The hard photons coming from the hot region heat the cold material mainly due to photoelectric absorption and to 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. The full details of this feedback mechanism will be presented elsewhere (Titarchuk, in preparation), while for our present purposes, 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 two luminosities are related by the expression

$$L_0 = 0.5(1 - A)L \quad (4)$$

where A is the albedo of the cold material. The expression for the monochromatic albedo 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

$$1 - A = \frac{\int_0^\infty (1 - A_\nu) F_\nu d\nu}{\int_0^\infty F_\nu d\nu} = \sqrt{\frac{\pi}{3}} \frac{kT_e}{m_e c^2} \frac{\Gamma(3/2 - \alpha)\Gamma(\alpha + 4.5)}{\Gamma(3/2)\Gamma(\alpha + 4)\Gamma(1 - \alpha)}. \quad (6)$$

Here α is the slope of the incident flux F_ν , while we have assumed, in accordance to our earlier discussion, that this flux is given by formulas (2) and (3) – or Eqn. (23) of ST80.

In addition to Eqn. (4), L and L_0 are related by the expression for the enhancement factor $d(\alpha)$ due to the upscattering of photons (ST80, 85)

$$\frac{L}{L_0} = d(\alpha)x_0^{\alpha-1} = \frac{\alpha(\alpha+3)\Gamma(\alpha+4)\Gamma(\alpha)\Gamma(1-\alpha)}{\Gamma(2\alpha+4)}x_0^{\alpha-1}. \quad (7)$$

Therefore one can eliminate L and L_0 from the equation above and solve at once for the frequency of soft radiation

$$x_0 = \left(\frac{1}{2} \sqrt{\frac{\pi k T_e}{3 m_e c^2}} \frac{\Gamma(3/2 - \alpha)\Gamma(\alpha + 4.5)\Gamma(\alpha)\alpha(\alpha + 3)}{\Gamma(3/2)\Gamma(2\alpha + 4)} \right)^{\frac{1}{1-\alpha}}. \quad (8)$$

Thus, by knowing the slope α and the temperature kT_e one can calculate at once the energy of the soft photons. Eqn. (8) holds provided that the energy deposition is due to the recoil effect, while it assumes that $x_0 \ll 1$ and $\alpha < 1$.

4. Fits to the observations

The recent OSSE observations of NGC 4151 (Maisack et al. 1993) represent the most sensitive observations of this object in the energy range from 60 keV up to 1 MeV. The emission spectrum of NGC 4151 is supposed to be the typical Comptonization spectrum formed due to upscattering of ultraviolet radiation reproduced in the cold material of the accretion disk (see e.g. Dermer et al. 1991).

Figure 1 shows the OSSE data and the best fit given by the analytic formulae (2) and (3) with a plasma temperature of 46^{+8}_{-2} keV and Thomson optical depth of $1.1^{+0.2}_{-0.13}$ for a plane geometry and of $2.9^{+0.4}_{-0.3}$ for a spherical geometry (χ^2 probability = 0.1). The best fit with $kT_e = 46.3$ keV and $\beta = 0.21$ gives $\chi^2 = 11.4$ for eleven points and $\chi^2 = 12.2$ in the case of higher temperature 55 keV and $\beta = 0.32$.

Figure 2 shows the OSSE (Maisack et al. 1993) and the Ginga (Yaqoob et al. 1993) results and the best theoretical fit with a plasma temperature of 44^{+4}_{-4} keV and $\beta = 0.186^{+0.028}_{-0.023}$. The corresponding Thomson optical depth are 1.25 in disk geometry and 3.2 in spherical geometry. The best fit with $kT_e = 44.1$ keV and $\beta = 0.186$ gives $\chi^2 = 33.03$ for twenty nine points and $\chi^2 = 35.4$ in the case of higher temperature 48.5 keV and $\beta = 0.214$. The absorber column density was kept fixed at the best-fit value given by Yaqoob et al. (1993), namely $N_h = 9.8 \times 10^{22} \text{ cm}^{-2}$.

Because the energy deposition in the cold matter is determined by the bulk of the incident energy flux (see Eqn. 6) we can use the nonrelativistic Comptonization model of

ST80 to describe the hard part of the energy spectrum, i.e. we can use the Eqns.(6)–(8) to find the value of the low–frequency energy x_0 . The position of x_0 depends on α and kT_e , which are provided by the spectral fitting of the data. Maisack et al. (1993) using the ST80 model give the best fitting parameters $\alpha = 1.0$ and $kT_e = 37$ keV for this model. But we take the larger temperature $kT_e = 45$ keV with the relevant parameter $\alpha = 0.9$ which are also consistent with this data, in order to estimate the energy bulk more accurately. Indeed, the ST80 model with the best fitting parameters does not provide enough photon flux at energies above 200 keV (Maisack et al. 1993). Assuming an X-ray luminosity equal to $10^{43} \text{ erg s}^{-1}$, and $\alpha = 0.9$, $kT_e = 45$ keV and using Eqn. (8) we produce the appropriate values of the soft photon blackbody temperature and the emission surface size: $kT_0 = 5$ eV ($h\nu_0 = 13.5$ eV) and $R = 1.8 \times 10^{13}$ cm.

5. Summary

In the present *Letter* we have presented a fit to the recent NGC 4151 OSSE observations based on the generalized Comptonization theory. While the fit is about as good as the fit one can derive from a straight application of the usual Sunyaev-Titarchuk formula, ST80 (Maisack 1993; Titarchuk and Mastichiadis, independent calculations), we find that with the new formula (3) one can fit better the data points in the higher energies. The temperature we derive from the fit is $\simeq 46$ keV, higher than the value of 37 keV derived using the non-relativistic ST formula (Maisack et al 1993). It is worth mentioning that electron temperatures in the range 40–50 keV would be consistent with those which are predicted by the two–temperature accretion scenarios (e.g. Eilek & Kafatos 1983).

Our conclusions, while not conclusive, point to 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 Seyferts –these annihilation lines are a signature for a certain class of non-thermal models , see for example Zdziarski & Lightman 1986. While some other non-thermal models (Mastichiadis & Kirk, to be submitted) 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.

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FIGURE CAPTIONS

Figure 1: The OSSE data of NGC 4151 (Maisack et al., 1993) and the best fit by Eqns. (2) and (3) –see text, with a plasma temperature of 46^{+8}_{-2} keV and Thomson optical depth of $1.1^{+0.2}_{-0.13}$ for the plane geometry and of $2.9^{+0.4}_{-0.3}$ for the spherical geometry (χ^2 probability = 0.1).

Figure 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 $\beta = 0.186^{+0.028}_{-0.023}$ and the appropriate Thomson optical depth are 1.25 in disk geometry and 3.2 in spherical geometry.

Fig. 1