Broad-band $\gamma$-ray and X-ray spectra of NGC 4151 and their implications for physical processes and geometry

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ABSTRACT
We study $\gamma$-ray observations of NGC 4151 by the Gamma Ray Observatory (GRO)/OSSE contemporaneous with X-ray observations by ROSAT and Ginga in 1991 June and ASCA in 1993 May. The spectra are well modelled by thermal Comptonization and a dual neutral absorber. We also find, for the first time for NGC 4151, a Compton-reflection spectral component in the Ginga/OSSE data. When reflection is taken into account, the intrinsic X-ray energy spectral index is $\alpha \sim 0.8$ and the plasma temperature is $\sim 60$ keV for both observations, conditions which imply an optical depth of $\sim 1$. The X-ray spectral index is within the range, $\alpha \approx 0.95 \pm 0.15$, observed from other Seyfert 1s. Also, the OSSE spectra of those and other observations of NGC 4151 are statistically indistinguishable from the average OSSE spectrum of radio-quiet Seyfert 1s. Thus, NGC 4151 observed in 1991 and 1993 has the intrinsic X-ray/$\gamma$-ray spectrum typical for Seyfert 1s, and the main property distinguishing it from other Seyfert 1s is a large absorbing column of $\sim 10^{23}$ cm$^{-2}$. We find no evidence for a strong, broad and redshifted Fe K$\alpha$ line component in the ASCA spectrum of 1993 May. Also, the Compton-reflection component in the Ginga/OSSE spectrum is a few times too small to account for the strength of the broad/redshifted line reported elsewhere to be found in this and other ASCA spectra of NGC 4151.

On the other hand, we confirm previous studies in that archival X-ray data do imply strong intrinsic X-ray variability and hardness of the intrinsic spectrum in low X-ray states. An observed softening of the intrinsic X-ray spectrum with the increasing flux implies that variability in $\gamma$-rays is weaker than in X-rays, which agrees with the 100-keV flux changing only within a factor of 2 in archival OSSE and GRANAT/SIGMA observations.

The relative hardness of the intrinsic X-ray spectrum rules out the homogeneous hot corona/cold disc model for this source. Instead, the hot plasma has to subtend a small solid angle as seen from the source of UV radiation. If the hot plasma is purely thermal, it consists of electrons rather than $e^\pm$ pairs. On the other hand, the plasma can be pair-dominated if a small fraction of the power is non-thermal.

Key words: galaxies: individual: NGC 4151 -- galaxies: Seyfert -- gamma-rays: observations -- gamma-rays: theory -- X-rays: galaxies.

1 INTRODUCTION
NGC 4151 is a nearby Seyfert 1.5 galaxy at $z = 0.0033$. In spite of its proximity and the wealth of X-ray and $\gamma$-ray data accumulated over the last 20 years, the nature of its nucleus remains poorly understood. Although it is the brightest Seyfert in hard X-rays it appeared to be distinctly different from average Seyfert 1s. Its X-ray spectrum is highly variable in the $2-10$ keV energy spectral index, $\alpha \sim 0.3-0.8$ (e.g. Yaqoob & Warwick 1991, hereafter YW91; Yaqoob et al.)
This hardness of the X-ray spectrum contrasts with typical Seyfert 1s, which have, on average, $\alpha=0.95\pm0.15$ (Nandra & Pounds 1994). Furthermore, no characteristic spectral upturn above $\sim 10$ keV owing to Compton reflection from cold matter, typical for Seyfert 1s (Nandra & Pounds 1994), was found in X-ray spectra of NGC 4151 from Ginga (Y93). In this work, we present and discuss results of the monitoring of NGC 4151 by the OSSE detector aboard the Gamma Ray Observatory (GRO) from 1991 to 1993. In 1991 June and 1993 May, the OSSE data can be supplemented by data in X-rays from ROSAT/Ginga and ASCA, respectively. These data suggest the intrinsic X-ray/$\gamma$-ray (hereafter abbreviated as $X_\gamma$) spectrum which is relatively steady in both the shape and amplitude, in contrast with many earlier observations in X-rays. We also study the presence of a Compton-reflection component and the form of the Fe K$\alpha$ line in the data, and consider the implications of archival X-ray data from EXOSAT, Ginga and GRANAT.

After presenting the data, we consider their implications for physical processes in NGC 4151. We study Comptonization in the $X_\gamma$ source as well as the presence of $e^\pm$ pairs and non-thermal acceleration. From that, we obtain strong constraints on the parameters and geometry of the central region of NGC 4151.

2 X-RAY/$\gamma$-RAY SPECTRA

We consider first two broad-band $X_\gamma$ spectra combining observations by OSSE in 1991 June/July and 1993 May with contemporaneous observations in X-rays by Ginga/ROSAT and ASCA, respectively. Then we consider other available data from OSSE, Ginga, EXOSAT and GRANAT.

2.1 Fitted models

We use XSPEC v9.0 (Arnaud 1996) for spectral fitting. The quoted errors are for 90 per cent confidence limits based on a $\Delta y^2=2.7$ criterion (Lampton, Margon & Bowyer 1976). Note that this confidence range corresponds to the probability that a fitted parameter exists in this range regardless of the values of all other parameters of a model (e.g. Press et al. 1992). Model parameters are given at $z=0.0033$.

We use the thermal Comptonization model of Lightman & Zdziarski (1987, hereafter LZ87) as the hard continuum model (see Appendix). The parameters of the model are the plasma temperature, $kT$, and the spectral index, $\alpha$, of the low-energy asymptotic power law. The second parameter is used instead of the geometry-dependent Thomson optical depth, $\tau$, of the plasma. As an alternative form of the continuum, we use a power-law spectrum with an exponential cut-off.

We allow for the presence of a Compton-reflection component in the spectrum, which arises when cold matter (e.g. an accretion disc) subtends a substantial solid angle as seen from the $X_\gamma$ source (Lightman & White 1988). We use angle-dependent reflection Green’s functions of Magdziarz & Zdziarski (1995) and allow the reflecting medium to be either neutral or ionized and with the same abundances as in the absorber (see below). The relative contribution of reflection is measured by the ratio, $R$, of the flux emitted towards the reflector to that emitted outward. Equivalently, $2\pi R$ gives the solid angle covered by the reflector as seen from the $X_\gamma$ source, with $R=1$ corresponding to an isotropic continuum source above a slab.

The continuum is modified by absorption. We use here a dual absorber model, i.e., the product of complete absorption (with the hydrogen column density $N_H$) and partial covering by neutral medium (with the hydrogen column $N_1$ and the covering factor $C_1$; e.g. Weaver et al. 1994, hereafter W94). We use the opacities of Balucinska-Church & McCammon (1992) and the abundances of Anders & Ebihara (1982). However, the ratio of the Fe abundance to that of Anders & Ebihara (1982), $A_{Fe}$, is a free parameter.

As an alternative, we also consider an ionized (‘warm’) absorber (Halpern 1984). We assume a model used by Done et al. (1992) but with the abundances of Anders & Ebihara (1982) instead of those of Lang (1974). Also, the iron edge energies are corrected (P. Życki, private communication) from the approximate values of Reimann & Mankowski (1979) to those of Kastra & Mewe (1993). The former authors employ the Hartree–Slater approximation, which is accurate to a few per cent only (e.g. their K-edge energy of neutral Fe is 6.9 keV instead of 7.1 keV). The corrected absorber opacities agree then with those of Balucinska-Church & McCammon (1992) in the limit of zero ionization. We assume an absorber temperature of $10^6$ K (Krolik & Kallman 1984). The ionization parameter is defined by $\xi=L/(nr^2)$, where $L$ is the 5 eV to 20 keV luminosity in an incident power-law spectrum and $n$ is the density of the absorber located at distance $r$ from the illuminating source.

NGC 4151 exhibits a strong soft excess component, whose complex nature is not fully understood (e.g. Warwick, Done & Smith, hereafter WDS95). We model it here as a Gaussian $(f_r)$ centred at $E_r=2$ keV, which provides good fits for both the 1991 June and the 1993 May data sets. The index of the soft power law, $\alpha_s$, is allowed to be different from that in the hard X-rays, which was found necessary by WDS95. This difference rules out the origin of the soft excess solely due to scattering by warm electrons external to the $X_\gamma$ source, which origin was proposed by W94. The soft component is absorbed by a neutral medium with the Galactic column density, $N_0=2.1\times10^{20}$ cm$^{-2}$ (Stark et al. 1992) except for the 1991 June observation.

NGC 4151 also emits an Fe K$\alpha$ line around 6.4 keV. We model it here as a Gaussian $(f_{Fe})$ centred at $E_{Fe}$ with a width of $\sigma_{Fe}$, total photon flux $I_{Fe}$ and absorbed in the same way as the continuum.

For the dual absorber, the model of the energy flux, $F_E$, has the form

$$F_E(E) = e^{-\sigma_{Fe}} [e^{-E_{Fe}/I_{Fe}}E^{-1-\alpha_s} + (1-C_1+C_1e^{-E_{Fe}/I_{Fe}})] I_E \text{ keV cm}^{-2} \text{ s}^{-1},$$

where $E$ is the photon energy in keV, $I_E$ represents the hard continuum including reflection, $I_r$ its 1-keV normalization, and $\alpha$ is the bound-free cross section of neutral matter. In the case of an ionized absorber, the two factors after the first ‘+’ sign in equation (1) are replaced by $e^{-\sigma_{Fe}N_1}$, where $\sigma_{Fe}$ is the bound-free cross section of ionized matter with the hydrogen column $N_1$.
2.2 1991 June

2.2.1 The data

NGC 4151 was observed by OSSE 1991 June 29–July 12. The observation was reported before by Madsack et al. (1993). The data used here have been obtained with the response matrix and calibration revised since then (see Johnson et al., in preparation). The response revision has resulted in the ~60–70 keV flux being about 10 per cent larger now. Also, the 50–60 keV channel data have been added.

The present data include estimated systematic errors. These systematics were computed from the uncertainties in the low-energy calibration and response of the detectors using both in-orbit and pre-launch calibration data. The energy-dependent systematic error was estimated at a value of three times the computed uncertainty and was added in quadrature to the statistical errors prior to spectral fitting. For NGC 4151, this systematic error is ~12 per cent of the statistical error at 50 keV and decreases to less than 0.1 per cent above 130 keV.

Close in time to the OSSE observation, NGC 4151 was observed by Ginga, 1991 May 31–June 2 (Y93), and by ROSAT, 1991 May 31–June 1. The Ginga (top-layer only) and ROSAT data have been analysed by WDS95. Here we use both the mid-layer and top-layer Ginga data (Turner et al. 1989), as obtained from the Leicester Ginga data base (D. Smith, private communication). The mid-layer and top-layer data are fully consistent with each other above 9 keV, and the mid-layer data are more accurate than the top-layer ones at ≥15 keV. We use Ginga data from a time interval overlapping with the ROSAT observation (see WDS95).

Note that this subset differs from the Ginga spectrum 'b' (in the notation of Y93), which was used in previous fits by Zdziarski, Lightman & Maciolek-Niedzwiecki (1993, hereafter ZLM93) and Titarchuk & Mastichiadis (1994, hereafter TM94). In order to allow for residual calibration uncertainties, we have added a 0.5 per cent systematic error to the Ginga data (Turner et al. 1989), and a 2 per cent error to the ROSAT data (WDS95). We then fit jointly the 0.2–2 keV ROSAT data, the 2–22 keV Ginga top-layer data, the 9–24 keV Ginga mid-layer data, and the 50–1000 keV OSSE data.

In the models below, we take into account the contribution to the Ginga spectrum from the BL Lac 1E1207.9 + 3945, which is located ~5 arcmin from the nucleus of NGC 4151 and is not resolved by Ginga. The BL Lac is resolved by ROSAT (WDS95), which observation yields a power-law spectrum with α ≃ 1.1 and a normalization implying an approximately 10 per cent contribution to the Ginga spectrum at 2 keV. (We arbitrarily assume the BL Lac power law is cut off exponentially with an e-folding energy of 300 keV; the value of this energy has negligible effect on our fits.)

2.2.2 Results

Our baseline model contains a hard continuum due to thermal Comptonization, a soft X-ray component, a dual absorber and a Kα line with energy and width of 6.4 keV and 0.1 keV, respectively (see Section 2.1). We first fix the Fe abundance at the solar value of Anders & Ebihara (1982).

We obtain an unacceptable fit with $\chi^2 = 194/126$ d.o.f. There are very strong residuals in the 4–10 keV range, which form an apparent broad line between 5 and 6 keV and an edge around 7 keV, as shown in Fig. 1(a). However, these systematic residuals disappear when the Fe abundance is allowed to vary (reaching $A_{Fe} = 2.8 \pm 0.3$; cf. YW91; Y93), as shown in Fig. 1(b). The reduction in $\chi^2$ is very large, to $\chi^2 = 99/125$ (at the continuum parameters of $\alpha = 0.74 \pm 0.002$ and $E_c = 54.9 \pm 5$ keV).

The residuals at $A_{Fe} = 1$ are explained by the presence of a strong K edge in the data, which causes the fitted local continuum to soften in order to account for the dip above the edge energy. This in turn gives rise to positive residuals below the edge and negative ones above it. The residual at ~6.5 keV is close to null because of compensation by an enhanced flux in the narrow ~6.4-keV line (~4 times stronger at $A_{Fe} = 1$ than at $A_{Fe} = 0.5$). Then the residuals between ~4 and 6.5 keV form a broad, line-like feature.

In order to test the uniqueness of the continuum shape obtained, we also fit a power law with an exponential cutoff. We obtain a much worse fit, with $\chi^2 = 112/125$ d.o.f., for $\alpha = 0.56$, e-folding energy $E_c = 121$ keV and $A_{Fe} = 3.5$. The model is a worse fit to both Ginga and OSSE data than is the thermal-Compton model. (The value of $\alpha$ is lower than that for the Comptonization model because of the different shapes of the high-energy cut-offs of the two models fitted to the OSSE data.) Since the cut-off power-law model gives a worse fit as well as failing to correspond to any physical process for the obtained parameters (see Section 3.1), we do not consider it any more.

We then compare our fits with the dual neutral absorber to those with a warm absorber (but keeping the soft X-ray component, see Section 2.1 and equation 1). We use thermal Comptonization for the hard continuum and allow for variable $A_{Fe}$. We obtain a fit with a harder intrinsic power law which is much worse statistically than that for the dual absorber: $\chi^2 = 155/126$ d.o.f. at $A_{Fe} = 1.5$ with 4–10 keV

![Figure 1](https://academic.oup.com/mnras/article-abstract/283/1/193/960595/195)

Figure 1. The 3–10 keV residuals to fits to 1991 June Ginga data. (a) The Fe abundance of Anders & Ebihara (1982). (b) The best-fitting Fe abundance. The broad ~5.5-keV feature apparent at the solar Fe abundance disappears now. See text.
residuals similar to those for the dual absorber at $A_{Fe} = 1$. The warm absorber also gives a bad fit to the ASCA data set of 1993 May. These results support those of Warwick et al. (1996), who found that the time-variability patterns of soft and hard X-ray variabilities are difficult to reconcile with the ionized absorber model. Also, Kriss et al. (1995) have found from the Hopkins Ultraviolet Telescope (HUT) data of 1993 May. These results support those of Warwick et al.

The warm absorber also gives a bad fit to the ionized absorber model. Also, Kriss et al. (1995) have found that the time-variability patterns of soft and hard X-ray variabilities are difficult to reconcile with the ionized absorber explained solely by strong photoionization of the X-ray absorber. Therefore, we decided to use the dual absorber model throughout. We note that a good fit of the warm absorber to the ROSAT/Ginga spectrum of NGC 4151 was obtained by WDS95 before the Fe iron edge energies have been corrected (see Section 2.1).

We then examine the presence of Compton reflection (Section 2.1). We assume first the inclination of $i = 65^\circ$, which is the minimum implied by HST observations of Evans et al. (1993). We find that adding a reflection component significantly improves the fit, reducing $\chi^2$ by 10.5, to 88.6/124 d.o.f. This corresponds to the probability of 0.02 percent that the fit improvement was by chance. The reflection fraction is $R = 0.43 \pm 0.22$. The spectrum is shown in Fig. 2(a) and the fit parameters are given in Table 1. We caution, however, that we do not directly see a hardening of the spectral slope above $\sim 10$ keV in NGC 4151 due to strong absorption, whereas such hardenings are seen in many other, less absorbed, Seyfert 1s (Nandra & Pounds 1994). Thus, the evidence for reflection in NGC 4151 is indirect, and the improvement of the fit may possibly be an artefact of our choice of models for the continuum and the absorber.

Reflection at $R = 0.43$ results in an increase of the fitted $kT$, from 54 keV to $88_{-25}^{+35}$ keV (but see Section 3.1), and an increase of the spectral index to $\alpha = 0.80_{-0.03}^{+0.05}$. The soft X-ray component is absorbed by $N_e = 3.3_{-0.3}^{+0.3} \times 10^{20}$ cm$^{-2}$. The best-fitting Fe abundance is lower when reflection is included, $A_{Fe} = 2.2_{-0.4}^{+0.4}$, because a part of the K edge is now accounted for by the reflection component.

We note that the Ginga top-layer data alone are consistent with the presence of reflection ($R = 0.47$ gives the best fit), but $R = 0$ is within the 90 per cent confidence interval. Addition of both the Ginga mid-layer data and the OSSE data strongly narrows that confidence interval. This is due, in particular, to the mid-layer data being more accurate than the top-layer data above $\sim 15$ keV, where the relative contribution of the reflection component peaks.

We have re-fitted the alternative models of an exponentially cut-off power law and of a warm absorber (see above), now including Compton reflection. We confirm that they provide much worse fits than our baseline thermal Compton, dual-absorber model even when reflection is included. For example, $\chi^2 = 102$ for the cut-off power-law model with reflection ($\alpha = 0.66$, $E_c = 150$ keV, $R = 0.38$) and the dual absorber, i.e., $\Delta \chi^2 = +13$ with respect to the corresponding thermal Compton model.

The relative reflection fraction depends on the viewing angle (Magdziarz & Zdziarski 1995). The value of $i = 65^\circ$ (Evans et al. 1993) is rather uncertain. Therefore, we also consider two other inclinations, in particular $i = 20^\circ$ (cos $i = 0.95$), which is the maximum inclination consistent with the Kz disc-line fits to ASCA data by Yaqoob et al. (1995, hereafter Y95). Inclinations of cos $i = 0.2$ and 0.95 give $R = 0.76_{-0.39}^{+0.39}$ and $0.24_{-0.12}^{+0.12}$, respectively, both with the

Table 1. Fit parameters for 1991 June and 1993 May observations for the thermal Compton model with Compton reflection. $I_{\nu}$, $I_{\nu}$ in $10^{-3}$ cm$^{-2}$ s$^{-1}$ keV$^{-1}$, $J_{Fe}$ in $10^{-2}$ cm$^{-2}$ s$^{-1}$; $N$ is in $10^{20}$ cm$^{-2}$, and $kT$ is in keV.

<table>
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<tr>
<th>Obs.</th>
<th>$kT$</th>
<th>$\alpha$</th>
<th>$R$</th>
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same $\chi^2$ as for $i = 65^\circ$. Note that the product $R \cos i$ (which determines the projected area emitting reprocessed UV flux; see Zdziarski & Magdziarz 1990), increases with $\cos i$; $R \cos i = 0.16, 0.18$ and 0.23 for $\cos i = 0.2, 0.42$ and 0.95, respectively.

We then examine the effect of ionization of the reflector. We model it in the same way as ionization of the warm absorber (see Section 2.1). We obtain $\zeta = 0.1^\circ.50$ erg s$^{-1}$ cm$^{-1}$, i.e., the reflector is close to neutral. Ionization reduces the fitted $R$, which becomes 0.32 only ($i = 65^\circ$) at the upper limit on $\zeta$.

Furthermore, the amount of reflection depends on the overall metal abundance (with respect to H and He). Its best-fitting value equals 1.0 (with the free Fe abundance), with the 90 per cent confidence upper limit at 1.9. At this limit, the relative reflection is only about 10 per cent larger than the solar abundances, e.g., $R = 0.27$ at $i = 20^\circ$. Thus, varying the overall metal abundance has only a small effect on the amount of Compton reflection. We have also tested the effect of replacing the abundances of Anders & Ebihara (1982) with those of Anders & Grevesse (1989). The main difference between the two is that the Fe abundance is about 40 per cent higher in the latter. We obtain virtually the same spectral parameters and values of $\chi^2$ for both abundances. The Fe abundance with respect to that of Anders & Grevesse (1989) for the model thermal Comptonization and neutral reflection is $A_{Fe} = 1.5^{+0.3}_{-0.2}$, which is just the range expected from rescaling the corresponding value in Table 1.

A Kx line is seen in the X-ray spectrum. Allowing the linewidth and energy to be free parameters, we obtain an insignificant reduction of $\Delta \chi^2 = -0.8$ at $E_p = 6.2$ keV and $\sigma_p = 0$ keV with respect to that at the fixed values of 6.4 and 0.1 keV, respectively. Thus, the data are consistent with the line being narrow and not redshifted. The equivalent width (EW) is $34^{+12}_{-7} \text{eV}$ (at $E_p = 6.4$ keV and $\sigma_p = 0.1$ keV, and defined with respect to the hard continuum only). The predicted EW of the line from reflection at the fitted $R \approx 0.4 \pm 0.2$ (for $i = 65^\circ$) is $\approx 60 \pm 30$ eV (George & Fabian 1991), which then constrains reflection to $R \approx 0.4$. This constraint can be relaxed if the line is broader or the reflecting medium is moderately ionized (Ross & Fabian 1993), possibilities that are allowed by the Ginga data. In order to test the former possibility we add a second, broad and redshifted, Gaussian component to the model (Y95). For $E_p = 5.7$ keV and $\sigma_p = 0.7$ keV, which are typical values obtained by Y95, we obtain $\Delta \chi^2 = -0.3$ only, i.e., the data allow but do not require a second component of the line. The allowed EW of the broad line is $30^{+20}_{-10}$ eV, which allows $R$ to be in the range derived from the continuum fit.

2.3 1993 May

2.3.1 The data

NGC 4151 was observed by OSSE on 1993 May 24–31. During that period, it was also observed by ASCA on 1993 May 25 (W94). OSSE observed no statistically significant variability of the 50–150 keV flux, with the test of the constant flux giving $\chi^2 = 0.22$ for 7 d.o.f., and the average flux having 2.5 per cent dispersion. Thus the week-long OSSE spectrum can be used together with the single-day ASCA spectrum. The OSSE spectrum has been processed in the same way as that of 1991 June (see Section 2.2.1).

We have extracted the spectra from the four ASCA detectors (SIS0, SIS1, GIS2 and GIS3) from the HEASARC archive using the ASCA software release of 1996 May (ascaarf v2.61). This corrects some inaccuracies of the detectors and telescope responses in the previous release (ascaarf v2.53). In particular, the effective area of the GIS detectors is now about 20 per cent lower, and an instrumental broad spectral feature around 6 keV is now corrected for.

We used the standard data-screening criteria to select good data (see W94). The extraction of SIS data was performed in rectangular regions covering parts of the chips 1 and 3 for SIS0 and SIS1, respectively. This maximized the usable SIS count rate from the observation, which was made in the 4-CCD mode with the source off-centre (see W94). Still, a relatively large number of counts could not be recovered, which significantly reduced the normalization of the obtained SIS spectra and rendered it unreliable (as noted by W94). Therefore, we use the GIS spectra (as corrected in ascaarf v2.61) for the absolute normalization. We note that the current GIS spectra yield the 8–10 keV fluxes about 1.2 times those obtained with the previous ASCA software (used, e.g., in Y95).

In fitting, we use the 0.4–10 keV GIS data, 0.8–10 keV GIS data and the 50–1000 keV OSSE data. The ASCA data are rebinned to have at least 20 counts per bin, as required for the validity of the $\chi^2$ statistics. Each of the four ASCA data sets is allowed to have free overall normalization, and the normalization of the OSSE data is tied to the average normalization of GIS2 and GIS3. Note that the ASCA data do not include systematic errors, which results in a relatively high $\chi^2$.

2.3.2 Results

We use the same models as in Section 2.2 to the combined ASCA/OSSE data. We first fit the model with thermal Comptonization, dual absorber, a soft X-ray component, free Kx line parameters, and no reflection. We obtain $\chi^2 = 1646 / 1683$ d.o.f. The hard continuum parameters, $z = 0.72^{+0.03}_{-0.02}$ and $kT = 63^{+13}_{-10}$ keV, as well its normalization, are very similar to the parameters of the corresponding model for the 1991 June data set (Section 2.2). We thus see that the intrinsic state of NGC 4151 in 1993 May is very close to that in 1991 June.

Since the 1991 June data show a Compton reflection component, we include it in the present data set as well. The energy range of the ASCA data precludes an independent determination of the strength of reflection and we simply fix it at the best-fitting value for the 1991 June data, $R = 0.43$. The model yields the same $\chi^2 = 1646 / 1683$ d.o.f. as for $R = 0$. The continuum parameters are now $z = 0.77^{+0.02}_{-0.02}$, $kT = 96^{+20}_{-25}$ keV, with the 1-keV normalization of $I_e = 8.6^{+0.8}_{-0.7} \times 10^{-5}$ cm$^{-2}$ s$^{-1}$, which are indeed the same within the statistical uncertainties as the corresponding parameters of the 1991 June observation (see Table 1). The data and model are shown in Fig. 2(b).

We have also tested a model with the ionized absorber instead of the dual neutral absorber, analogously to the 1991 June data (Section 2.2.2). We find that model gives a
much worse fit, with $\Delta \chi^2 = +128$ (at free $E_x$ and the absorber temperature of $10^5 \text{ K}$; $\Delta \chi^2 = +67$ at $10^6 \text{ K}$). The residuals for the fit resemble those shown in Fig. 1. Thus, ionized absorption does not provide a good model for the X-ray data.

We find that the soft X-ray component in the spectrum of NGC 4151 is also consistent with being constant. The 0.5–1 keV flux is $\approx 2 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ for both 1991 June and 1993 May observations. Note that contributions from extended soft X-ray emission (e.g. Morse et al. 1995) are different for each of the observations, which accounts for at least some of the small differences in the soft X-ray spectra seen in Fig. 2. We also note that although the soft X-ray excess in the ROSAT/Ginga data (Section 2.2) can be fitted by bremsstrahlung better than by a power law (WDS95), bremsstrahlung at the same temperature provides a bad fit to the soft X-ray excess in the ASCA data ($\Delta \chi^2 = +58$). On the other hand, the model of equation (1) provides a good description of both data sets.

The two spectra strongly differ, however, in absorption and in the strength of the Kα line. The column density of the partial coverer is now about a factor of 2 larger, $N_x \approx 1.4 \times 10^{25} \text{ cm}^{-2}$, and the Kα line is now much stronger, $E_{\text{Fe}} = 5.8 \pm 0.2 \text{ keV}$, than in 1991 June. This is suggestive of the difference in the line strength between the two spectra, $\Delta E_{\text{Fe}} \approx 200 \text{ eV}$, being due to emission by the additional absorption column in 1993 May (Makishima 1986). The parameters of the line are $E_{\text{Fe}} = 6.36 \pm 0.10 \text{ keV}$, $\sigma_{\text{Fe}} = 0.16 \pm 0.09 \text{ keV}$. This corresponds to the range of cloud velocities of $\Delta v \approx 18 \pm 6 \times 10^3 \text{ km s}^{-1}$ (Lang 1974), which suggest clouds at $\gtrsim 10^3 \text{ Schwarzschild radii}$.

On the other hand, Y95 has found that the Kα line in this observation is very broad and redshifted, which would suggest its origin from Compton reflection. As pointed out by Y95, NGC 4151 has a complex continuum shape, and the choice of the continuum model affects results regarding the line. In particular, the soft X-ray continuum is poorly understood, and our model of it is only phenomenological. Thus, we follow Y95 in constraining detailed fits of the Kα line to the range to $\gtrsim 3 \text{ keV}$ (but we use the OSSE data as a constraint on the continuum). We freeze $z$, $I$, and $N_x$ (which determine the shape of the spectrum below 3 keV) at the values obtained by fitting the whole ASCA energy range (Table 1). The single-line fit now gives $\chi^2 = 1158/1231 \text{ d.o.f.}$, and the line parameters are similar to those above, $E_{\text{Fe}} = 6.36 \pm 0.04 \text{ keV}$, $\sigma_{\text{Fe}} = 0.13 \pm 0.09 \text{ keV}$, $E_{\text{Fe}} = 220 \pm 20 \text{ eV}$. (Other parameters of interest are $z = 0.79$, $kT = 110 \text{ keV}$, $A_{\text{Fe}} = 1.5 \pm 0.3$.) Fig. 3 shows the resulting 3–10 keV residuals, with no systematic deviations in the 5–6 keV range. Indeed, adding a second Gaussian (with three free parameters) improves the fit by only $\Delta \chi^2 = -3$, which is statistically insignificant. The parameters of the second line are $E_{\text{Fe}} = 5.8 \text{ keV}$, $\sigma_{\text{Fe}} = 0 \text{ keV}$ (poorly constrained owing to the fact that such a line is not required by the data) and $E_{\text{Fe}} = 25 \pm 20 \text{ eV}$, i.e., the redshifted line component is much weaker than the main one. Thus, the presence of a broad and redshifted line component with a strength comparable to that of the narrow component is ruled out. This contrasts with the result of Y95, who obtained a fit improvement of $\Delta \chi^2 = -26$ due to adding a broad and redshifted Gaussian with the equivalent width similar to that of the narrow line.

In order to find the cause of this difference in the results, we have repeated the above analysis of the lineshape using the same PHA files and response files as those used by Y95. We are still able to obtain a satisfactory fit with our single-line model, which gives $\chi^2 = 0.97$ in the 3–10 keV range, which is the same as $\chi^2$ obtained by Y95 for their two-line model. No residuals in the 5–6 keV are seen for that model. Adding a second Gaussian results indeed in a negligible fit improvement, $\Delta \chi^2 = -4$, similarly as in the case of our ASCA data. This shows that a major cause of the difference between our results and those of Y95 is the difference in the choice of continuum. We use a power law (see Section 3.1) attenuated by a dual neutral absorber with variable Fe abundance whereas Y95 has chosen an analytic function designed to reproduce a power law and an ionized absorber. A possible strong effect of changing the absorption law in the presence of a broad, redshifted line is illustrated in Fig. 1. One difference between the results based on the two data sets is that the broad, redshifted, Gaussian fitted to the data of Y95 has $E_{\text{Fe}} = 180 \text{ eV}$, which is of the same order as the EW of the narrow line. Such a strong feature is ruled out in our current ASCA data. This is explained by the difference between ascaarf v2.53 and 2.61 (see Section 2.2.1).

However, most of the statistical evidence of Y95 for the presence of a strong broad-line component in NGC 4151 comes from 1993 December observation, with the exposure time of 41.2 ks, compared to 15.5 ks in 1993 May. Thus, our conclusions regarding the weakness of a broad line need to be confirmed by studying longer-exposure spectra, e.g. the 1993 December one. We also stress that other Seyferts with a broad line seen in the ASCA data, e.g. MCG 6-30-15 (Tanaka et al. 1995), have much less absorption than NGC 4151 and thus the shapes of their broad lines are very weakly dependent on details of absorption.

Finally, we note that the data above 3 keV are fitted with $A_{\text{Fe}} = 1.5 \pm 0.3$, which is consistent with $A_{\text{Fe}} = 2.2 \pm 0.4$ in 1991 June for $A_{\text{Fe}} = 1.8$. Thus, $A_{\text{Fe}} = 1.8$ is the Fe abundance consistent with our two sets of data. On the other hand, a change of fitted $A_{\text{Fe}}$ may result from our idealized modelling of absorption.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** The 3–10 keV residuals to the single-line fit above 3 keV to 1993 May ASCA/OSSE data. No broad, redshifted component of the Kα line is seen. The data from all four ASCA detectors have been added for plotting. See Section 2.3.2.

### 2.4 Other data

The 1991–1993 OSSE observations of NGC 4151 show a remarkable constancy in γ-ray flux with time (see Section...
2.4.1 OSSE data

All up-to-date observations of NGC 4151 by OSSE are presented in detail by Johnson et al. (in preparation). Here we consider the data from four viewing periods (hereafter VP) until the end of 1993, namely 1991 June 29–July 12 (VP 4), 1993 April 20–May 3 (VP 218), 1993 May 24–31 (VP 222) and 1993 December 1–13 (VP 310; from Warwick et al. 1996).

All the data are well fitted by the thermal Comptonization model with reflection. However, we present here fit results with an exponentially cut-off power law (which fits the OSSE data alone equally well), in order to give a convenient representation of the γ-ray spectra. We stress that this phenomenological model should not be extrapolated below 50 keV, and that α cannot be interpreted as the X-ray spectral index implied by the data. Table 2 shows the fit results as well as the photon fluxes in the 50–100 and 100–200 keV bands. We see that all the spectra are approximately compatible with the constant shape, and the fluxes vary within ±10 per cent only. All four data sets can indeed be well fitted ($\chi^2_{\text{red}} = 0.73$) with the same model at free normalization as shown in Table 2.

Table 2 also shows the fit results for the average spectrum of all radio-quiet Seyfert 1s observed so far by OSSE with the exception of NGC 4151 (McNaron-Brown et al., in preparation). That spectrum has been obtained using the current OSSE response. The response revision has resulted in an overall spectral softening with respect to the average Seyfert spectrum presented by Johnson et al. (1994). We see that thespectral parameters are consistent with those of NGC 4151 within the statistical uncertainties, as pointed out by Johnson et al. (1994). This can be quantified by fitting simultaneously the average Seyfert 1 spectrum together with all four spectra of NGC 4151. We find that the fit is then almost identical to that for the four NGC 4151 spectra at $\Delta \chi^2 < 1$ with respect to the $\chi^2$ sum of the previous two individual fits. Thus, the OSSE data do not show a difference between the spectra of NGC 4151 and that of the average Seyfert 1 sample. We have also obtained the same results for the average radio-quiet Seyfert 1 spectra based on smaller samples of objects observed by both Ginga and OSSE and by EXOSAT and OSSE (five and seven objects, respectively; Gondek et al. 1996).

2.4.2 Ginga and EXOSAT data

The 2-keV flux in EXOSAT and Ginga data changes by a factor ∼ 35 (Fig. 4; Pounds et al. 1986; Yaqoob, Warwick & Pounds 1989; YW91; Y93). During the 1991–1993 monitoring of NGC 4151 by OSSE, four X-ray observations (Y93; W94; Y95; Warwick et al. 1996) show the 2-keV flux varying within a factor ∼ 5 in a lower part of the flux range observed by EXOSAT and Ginga.

If the γ-ray flux were universally close to constant, one should be able to fit the archival Ginga data together with the current OSSE data. We use both top-layer and mid-layer Ginga data. We first consider the data with the highest 2–10 keV X-ray flux, which were obtained 1990 May 15–16 (Y93). Fig. 4 shows the fit of the thermal Comptonization model with reflection to the archival NGC 4151 data together with the range of γ-ray states seen by OSSE (not simultaneous; thin and thick crosses at 30 keV) and EXOSAT (circled crosses) together with the range of γ-ray states seen by OSSE (not simultaneous; thin and thick symbols above 50 keV). The solid curve represents the thermal Comptonization model, which fits the combined highest Xy data. The dashed and dotted curves represent fits of the same model to the lowest Ginga and EXOSAT data, respectively, which both imply ∼50-keV fluxes below the range seen by OSSE. See text.
model. For models in this section, the soft excess component is fixed at the shape obtained for the 1991 June data (Table 1), and the column $N_{\text{H}}$ is constrained to $\geq 10^{22}$ cm$^{-2}$ to avoid having the hard X-ray continuum component appear below $\sim 1$ keV (see YW91). We use the OSSE 1993 May 24–31 data, which have the highest 50–200 keV flux. We obtain $\beta = 0.84 \pm 0.05$ and $kT = 78 \pm 4$ keV at $\chi = 84/104$ d.o.f., i.e., the data are very well fitted by the model. Thus, the highest observed X-ray and $\gamma$-ray states are compatible with each other. There is no reflection component at X $\sim 200$ A. A. Zdziarski, W. N. Johnson and P. Magdziarz

2.4.3 GRANAT data

NGC 4151 was observed from 1990 July to 1992 November by the GRANAT satellite (Finoguenov et al. 1995). In particular, it was observed by the ART-P (below 30 keV) and SIGMA (above 30 keV) instruments on 1991 June 29 and July 11–12, i.e., contemporaneously with the OSSE observation of 1991 June 29–July 12. The GRANAT, OSSE and Ginga observations are compared in Fig. 5. We see that the OSSE and SIGMA data are consistent with each other. On the other hand, the ART-P data are somewhat above the corresponding Ginga data. The cause of that may be X-ray variability (since the Ginga data are from about a month earlier) as well as uncertainty in the relative calibration of the instruments. Still, the Ginga data match very well the OSSE data (see Fig. 2a), and the slow variability seen in the OSSE range (Section 2.4.1) is compatible with the spectrum above 50 keV during the Ginga observation being indeed at the level measured 1 month later.

SIGMA has observed an almost constant $\gamma$-ray flux from NGC 4151 during four out of five observations (Finoguenov et al. 1995). During those observations, $EF_{E}$ at 100 keV was $\sim 0.16 \pm 0.05$ keV cm$^{-2}$ s$^{-1}$. In 1991 November, the flux of $0.30 \pm 0.04$ keV cm$^{-2}$ s$^{-1}$ was observed. The corresponding range in the 1991–1993 OSSE observations is $0.18 \pm 0.01$ to $0.25 \pm 0.01$ keV cm$^{-2}$ s$^{-1}$. Thus, although the SIGMA data by themselves indicate stronger variability than the OSSE data, the two data sets are consistent with each other within measurement errors.

Summarizing, the EXOSAT, Ginga and GRANAT results strongly suggest that the fluxes between 50 and 100 keV vary at least within a factor of 2, which is more than the range observed by OSSE in 1991–1993. The strongest prediction is that of $EF_{E}(50$ keV)$=0.12 \pm 0.02$ keV cm$^{-2}$ s$^{-1}$ from extrapolation of the lowest Ginga spectrum, the $EF_{E}$ of

Figure 5. Comparison of observations of NGC 4151 by GRANAT 1991 June 29 and July 11–12 (thick symbols), by OSSE June 29–July 12 (thin symbols above 50 keV), and by Ginga May 31–June 1 (thin crosses below 30 keV).
which is a factor of 2 below the lowest 1991–1993 OSSE flux of \(0.24 \pm 0.01\) keV cm\(^{-2}\) s\(^{-1}\). This fact is confirmed by OSSE observation of a low > 50 keV state in 1995 (Johnson et al., in preparation).

### 3 THEORETICAL IMPLICATIONS

#### 3.1 Source parameters and geometry

Our thermal Comptonization model uses \(\alpha\) and \(kT\) as free parameters. The plasma optical depth, \(\tau\), is geometry-dependent. To determine it accurately for a uniform spherical source, we use a Monte Carlo method (see Appendix). We will use throughout the continuum parameters derived for 1991 June as the parameters for 1993 May are very similar, see Table 1.

We find that the spectrum observed in 1991 June (with \(\alpha = 0.80\) and \(kT = 88\) keV) corresponds to that from Comptonization in a uniform sphere (with a uniform distribution of seed-photon sources) with \(kT = 61\) keV and \(\tau = 1.3\). The temperature is lower than that obtained from fitting because the Comptonization model is formally obtained under the assumption of \(\tau^2 \gg 1\), whereas \(\tau\) now approaches unity. Still, that model gives a very good description of the shape of the spectrum, albeit for a somewhat different temperature, as shown in Fig. 6. Thus, the fit results for \(kT\) in Table 1 need to be rescaled by about 2/3, similarly to the case of the approximation of emission from optically thin plasmas by a power law with an exponential cut-off (Zdziarski et al. 1994). (However, a power law with an exponential cut-off does not approximate emission from plasmas with \(\tau \gtrsim 1\).) The agreement of the parameters of our model with those derived from the Monte Carlo method improves rapidly with increasing \(\tau\) (see Appendix).

The plasma cloud is irradiated by soft photons providing seeds for Comptonization. We take the seed photons as a diluted blackbody distribution at the temperature of 5 eV (Kriss et al. 1995; Zdziarski & Magdziarz 1996). The ratio of the Comptonized flux to the soft flux irradiating the plasma is 13, i.e., the plasma is soft-photon starved. Some or all of the seed photons are due to reprocessing of the Comptonized hard radiation by cold matter, e.g., an accretion disc. We consider this effect here and find that the X\(\gamma\) source cannot, contrary to a claim of TM94, form a homogeneous corona above the surface of an accretion disc.

A hot corona above a cold disc is cooled by soft photons emitted by the disc. The soft emission is due to both internal dissipation in the disc and reprocessing of hard radiation from the corona irradiating the disc. The cooling is minimized when all the dissipation occurs in the corona and none in the disc (Haardt & Maraschi 1993), which case we consider below. Anisotropy effects (Haardt 1993) are small at our derived plasma parameters and the corona emits photons approximately equally upwards and downwards (towards the disc). The downwards part is mostly absorbed and re-emitted as the seed thermal UV radiation. The seed photons are upscattered, which self-consistently forms the X\(\gamma\) corona emission. Since the seed photons are from the reprocessed \(~50\) per cent fraction of the corona photons emitted downwards, the observed X\(\gamma\) luminosity, \(L_{X}\), (from the \(~50\) per cent of the corona photons emitted upwards), equals approximately the UV disc luminosity, \(L_{UV}\).

This condition is strongly violated in NGC 4151, in which \(L_{UV} \ll L_{X}\) (see above). We have performed detailed Monte Carlo calculations of a slab of hot electrons above a cold disc. For the spectral parameters for the 1991 June observation, we find the full slab thickness corresponding to \(\tau \approx 1.3\). The slab luminosity directed downwards is 8.0 times the seed UV luminosity, \(L_{UV}^{seed}\). Then we compute the integrated albedo of the cold disc, \(A = 0.22\). Thus, the UV emission of the cold disc from reprocessing of the corona hard emission is \(8(1 - 0.22) \approx 6.2\) times the seed UV luminosity, i.e., \(L_{UV}^{processed} \approx 6L_{UV}^{seed}\). This strongly violates the energy balance condition, \(L_{UV}^{seed} \approx L_{UV}^{processed}\). The above discrepancy in the luminosities is much worse for the spectrum used by TM94, which is much harder than our intrinsic spectrum, and thus much more soft-photon starved. Furthermore, any power internally dissipated in the disc will worsen this discrepancy. Thus, the high-energy source in NGC 4151 cannot form a homogeneous corona, contrary to TM94. The discrepancy is due to TM94 both neglecting bound–free absorption in their albedo (which underestimates the absorbed fraction, \(1 - A\)) and using the formulae of Titarchuk (1994) derived under the assumption of \(1 - A \ll 1\) (while the actual \(1 - A \approx 0.8\)). (We also note that \(\tau = 1.25\) given in TM94 as the optical depth of their hot corona is in fact the half-thickness of the corona on each side of the disc.)

Thus, the spectrum of NGC 4151 requires that the reprocessed UV radiation returning to the hot source(s) is reduced to \(\sim 0.2\) with respect to that from a hot slab located above a cold slab. This soft-photon starvation can be achieved by geometry. The source can form one or more clouds at some height above the disc (e.g., Svensson 1996). For a suitable ratio of the height to the source size, only \(\sim 20\) per cent of the reprocessed emission returns to the hot source. (Note that this geometry is different from the patchy coronae of Haardt, Maraschi & Ghisellini 1994 and Stern et al. 1995, in which X\(\gamma\) sources are close to the disc surface and most of the reprocessed emission does return to the hot source.) On the other hand, the disc-corona geometry

![Figure 6. The Comptonization spectrum from a spherical plasma cloud with parameters corresponding to 1991 June. The solid curve gives the spectrum of the fitted continuum models and squares give results of our Monte Carlo simulations (see text). The model spectrum agrees very well with Monte Carlo simulations. The dashed curve represents the seed diluted-blackbody photons with the temperature of 5 eV.](image)
would imply a Compton reflection component with $R \sim 1$, which is more than that observed (unless for an edge-on orientation; Sections 2.2, 2.4.2). If the cold medium is Thomson-thick, the weakness of Compton reflection implies that the cold medium covers at most a $\sim 1\pi$ solid angle as seen from the hot source. A geometry compatible with both soft photon starvation and reduced reflection is a hot inner disc and a cold outer disc (e.g., Shapiro, Lightman & Eardley 1976). Alternatively, the covering by the cold medium could be higher if the medium is Thomson-thin. Also, the hardness of the X-ray spectrum together with the relative weakness of Compton reflection is compatible with some configuration of hot and cold clouds with mutual covering factors less than unity.

3.2 Electron–positron pairs

Here we examine if the hot source in NGC 4151 is dominated by $e^\pm$ pairs or by electrons. The pair production rate depends on the shape and the amplitude of the spectrum (Gould & Schréder 1967). On the other hand, the pair annihilation rate depends on the optical depth of the source. The two quantities are equal in pair equilibrium, which is established under most conditions even in variable sources (Svensson 1984).

We first assume that the X$_\gamma$ emission is purely a result of thermal Comptonization. We use the Comptonized spectrum with the parameters as for 1991 June (Table 1) to compute the total pair production rate (Gould & Schréder 1967). This rate scales with the size of the X$_\gamma$ source, $r_{X\gamma}$, as $r_{X\gamma}^{-1}$. On the other hand, the pair annihilation rate scales as $r_{X\gamma}^{2}$. Requiring the pair equilibrium we can solve for $r_{X\gamma}$. Assuming a spherical pure pair source and setting the average photon escape time to $r_{X\gamma}/c$ we obtain a value of $r_{X\gamma} = 2.2 \times 10^{11}$ cm. The X$_\gamma$ luminosity is $L_{X\gamma} \approx 5 \times 10^{45}$ erg s$^{-1}$, and the corresponding compactness parameter is very large, $\ell \sim 10^{6}$, where $\ell \equiv L_{X\gamma} / r_{X\gamma} c L_{\text{e}}$ (Svensson 1984). Thus, the required size of the pair source is rather small, and much less than the characteristic size of 10 Schwarzschild radii, $10 r_{s} \sim 10^{13}$ cm implied by the black hole mass estimate of $\sim 4 \times 10^{7} M_\odot$ of Clavel et al. (1987). Even the size inferred from the minimum possible mass from the condition of sub-Eddington luminosity during the highest states of the source (Section 2.4), $10 r_{s} \sim 10^{13}$ cm, is still much more than the required size of the pair source. Furthermore, the Eddington limit is reduced for pair-dominated sources (Lightman, Zdziarski & Rees 1987), in which case $10 r_{s} \gg 10^{13}$ cm. This would imply that most of the bolometric luminosity (which is mostly in X$_\gamma$ photons) is emitted from a region much smaller than the region in which most of the gravitational energy is released, which seems unlikely.

Thus, if the X$_\gamma$ source in NGC 4151 is thermal, it consists most likely of $e^-$ rather than $e^\pm$ pairs. Note that the situation in NGC 4151 differs strongly from that assumed in the models of Seyfert 1s of Stern et al. (1995). That study considers plasmas hotter and more optically thin than that found here for NGC 4151, which results in $\ell \sim 10^{5}$ being already sufficient for the dominance of pairs.

On the other hand, ZLM93 considered a hybrid, thermal/non-thermal, model for NGC 4151, in which a small fraction of the electrons or $e^\pm$ pairs in the source is accelerated to non-thermal, relativistic, energies, but the bulk of the spectrum is still produced by thermal Comptonization. In the limit of zero non-thermal fraction (i.e., uniform heating of all electrons in the source), the model yields a pure thermal Comptonization spectrum. Acceleration has a two-fold role in the model. First, Compton scattering by non-thermal electrons as well as $e^\pm$ pair annihilation give rise to a weak tail on top of the thermal Comptonization spectrum. [This contrasts the purely non-thermal pair model proposed earlier to explain the Ginga spectra of typical Seyfert 1s (Zdziarski et al. 1990), in which most of the X$_\gamma$ spectrum is a result of non-thermal Comptonization.] Secondly, pair production by $\gamma$-rays in the tail can supply some or all of the thermal electrons/pairs in the source.

ZLM93 found that addition of a tail from non-thermal acceleration improves the fit to the Ginga/OSSE spectrum of 1991 June above $\sim 200$ keV. However, the plasma temperature in our present model (Table 1) is much above $kT \sim 40$ keV obtained by ZLM93. The present higher value is due to inclusion of Compton reflection, the revision of the OSSE response, as well as using a better absorber model. Consequently, our present model spectra (see Fig. 2) have a much more gradual high-energy cut-off than that of the spectrum of ZLM93. Thus, a spectral tail in our present model is not required.

However, an attractive feature of the hybrid model is that it can provide the electron optical depth needed for thermal Comptonization self-consistently. We find that the non-thermal compactness, $\ell_{\text{nth}} \equiv L_{\text{nth}} L_{\text{e}} (r_{X\gamma} / c L_{\text{e}})$ (where $L_{\text{nth}}$ is the non-thermal luminosity), required to produce pairs that have the required optical depth is $\ell_{\text{nth}} \approx 10$, approximately independently of the total compactness. The non-thermal fraction, $f_{\text{nth}} L_{\text{nth}} / L_{\text{e}}$, is constrained to be small by the form of the cut-off in the $\gamma$-spectrum. For the Ginga/OSSE spectrum, we obtain $f_{\text{nth}} L_{\text{nth}} / L_{\text{e}} \approx 0.08 \pm 0.04$ in a model with non-thermal electrons accelerated to the Lorentz factor of $10^{2}$.

The best fit corresponds to a pure pair source with $\ell \sim 140$ and $\Delta \gamma^2 = -0.5$ with respect to the purely thermal model, and the lower limit corresponds to the pure thermal-$e^-$ source.

Thus, the source can be dominated by $e^\pm$ pairs if just $\sim 10$ per cent of the available power is released non-thermally. Such a situation is likely if the X$_\gamma$ emission is from magnetic flares, in which reconnection can accelerate electrons. The characteristic compactness is $\ell \sim 10^{5}$, which corresponds to $r_{X\gamma} \approx 2 \times 10^{13}$ cm, which is then compatible with the estimates of the source size above. The compactness of $\ell \sim 100$ is superEddington for a pure pair source and thus we can rule out such a case. However, just $\sim 10$ per cent of protons in a pair-dominated source can provide the needed gravitational confinement of the plasma at that compactness (Lightman et al. 1987). Thus, the hybrid model described above is still a viable alternative to the pure thermal-$e^-$ model.

4 DISCUSSION AND CONCLUSIONS

Observations discussed in this paper fall into two groups. First, we have found that the intrinsic spectra of NGC 4151 in 1991 June and 1993 May are the same within the observational uncertainties. This intrinsic spectrum is rather typical for Seyfert 1s (Nandra & Pounds 1994; Zdziarski et al. 1996).
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June reflection component, and the soft γ-ray spectrum with reflection component at least in some states (confirming shape indistinguishable from other Seyfert Is. This is a new show the intrinsic X-ray spectrum to be strongly variable, fraction cannot be increased by varying either the Fe abundance.

In spite of the similar continua in the 1991 and 1993 spectra, the Fe Kα line is much stronger in the 1993 observation, in which X-ray absorption is also stronger. The line in 1993 is narrow, and any broad and redshifted component (not required by the data) is constrained to less than 20% of the narrow component. The narrowness of the line in the 1993 observation, together with the lack of the correlation between the strength of the continuum and that of the line, suggests that the origin of most of the line photons is from absorption rather than reflection. This is consistent with the relatively weak reflection in the 1991 June data.

The Xγ continuum is very well modelled by thermal Comptonization of soft UV photons by a plasma with τ = 1 and kT ~ 60 keV (Section 3) and attenuated in X-rays by a dual neutral absorber (which approximates absorption by a distribution of clouds). We have considered alternative models with an exponentially cut-off power law instead of the Comptonization spectrum as well as with an ionized absorber instead of the dual neutral absorber. We have found those alternative models give a much worse description of the data.

Another alternative model of the X-ray spectra in 1991 June and 1993 May has been proposed by Poutanen et al. (1996), hereafter P96). They assumed the intrinsic Xγ emission to be completely attenuated by an optically thick medium, and the observed emission to arise from scattering towards our line of sight by an optically thin plasma, similarly as in the unified model of Seyfert 2s (e.g., Antonucci 1993). The shape of the observed spectrum is that of the intrinsic one at low energies, but it has an additional cut-off due to the Klein–Nishina scattering at high energies (e.g., Jourdain & Roques 1995). P96 consider two intrinsic emission models. One is a power law (α = 0.67 ± 0.057, which is harder than the Seyfert 1 average) with an exponential cut-off and reflection (as well as a soft X-ray component and a Kα line), and the other is a self-consistent disc–corona emission model (with kT ~ 300 keV). Both models have high-energy cut-offs at several hundred keV, which corresponds to the average spectrum, with α ~ 0.9, of Seyfert 1s (Zdziarski et al. 1995; Gonidakis et al. 1996). The models fitted to the ROSAT/Ginga/OSSE data of 1991 June (but without the Ginga mid-layer data) yield χ^2 = 114/100 and 110/101 d.o.f., respectively. Those fits are much worse than those obtained by us (Section 2.2.2).

Since P96 use a different model for the soft X-ray component and do not show their residuals or the contributions to χ^2 from each detector, it is difficult to establish the cause of the large difference in χ^2. However, the self-consistent disc–corona model plotted in P96 clearly overpredicts the spectrum around 20 keV, and it appears to give a worse fit to the OSSE data than our model does. P96 also fit their model to the ASCA/OSSE data of 1993 May. However, they use the SIS0 data with their own normalization, which is known to be incorrect (W94). That normalization is, in fact, a factor ~ 2 less than that of the correct spectrum (Fig. 2b), and thus we do not compare our results for 1993 May with those of P96.

The difficulties in fitting the scattering, Seyfert 2-like model to NGC 4151 appear to reinforce our conclusion that NGC 4151 as observed in 1991 and 1993 is intrinsically a Seyfert 1 with an average Xγ spectrum. The spectral index of α ~ 0.8 is within the 1σ range of Seyfert 1s, 0.95 ± 0.15 (Nandra & Pounds 1994). Also, the OSSE spectra of NGC 4151 are statistically the same as the average spectrum of weaker radio-quiet Seyfert 1s observed by OSSE. The fact that the OSSE spectra of NGC 4151 are fitted with a high-energy cut-off energy lower than that of the average Seyfert 1 Xγ spectrum is explained by a correlation between α and the cut-off energy. The correlation appears because harder X-ray spectra (such as of NGC 4151) need to be cut off faster than softer X-ray spectra in order to fit the same γ-ray spectrum.

The X-ray spectrum of NGC 4151 is too hard for the homogeneous disc–corona model of Haardt & Maraschi (1993) to apply. (We find that the disc–corona model applied to NGC 4151 by TM94 is in error.) We find the Xγ source in NGC 4151 subtends a small solid angle of ~ 0.2 x 2π as seen from the UV source (providing seed photons for Comptonization). This also rules out patchy corona models with the Xγ sources located on the surface of the disc. The possible geometries are either the Xγ sources at a large enough height above the surface of an accretion disc (e.g., Svensson 1996), a hot inner disc, or the UV-emitting cold matter in the form of clouds.

Similar geometries have been considered by Zdziarski & Magdziarz (1996) as models for the UV/X-ray correlation observed in NGC 4151 by EXOSAT and IUE (Perola et al. 1986). Their transmission model explains the correlation as being due to the X-ray absorber re-emitting the absorbed X-ray power in the UV. The source parameters obtained here for the 1991 June and 1993 May data are consistent with that model. In particular, the width of the Kα line implies its origin at ~ 10 Schwarzschild radii (Section 2.3.2), which is compatible with the UV response to varying X-rays delayed by ~ 0.3 d (Edelson et al. 1996) for the black hole mass of ~ 10^7 M⊙. Unfortunately, no UV data exist for the Xγ observations studied here. The reflection model of Zdziarski & Magdziarz (1996) explains the correlation as UV re-emission of Xγ emitted towards a cold disc by a patchy corona. That model is independent of the corona geometry, and thus it is compatible with the photon-starved corona required by the spectra reported here. The model also requires that R cos i ≥ 0.15, which condition is satisfied for the 1991 June observation (Section 2.2.2). We intend to test the models of Zdziarski & Magdziarz (1996) against the 1993 December IUE/ROSAT/ASCA/OSSE data (Edelson et al. 1996; Warwick et al. 1996).
The parameters of the $X\gamma$ source ($\tau \sim 1$, $kT \sim 60$ keV, Section 3.1) imply that pair production is negligible if the plasma is thermal (Section 3.2). On the other hand, a small fraction of the total power used to accelerate electrons to relativistic energies results in enough pair production for the plasma to be pair-dominated. Such acceleration may take place in magnetic flares, which are likely to be responsible for the formation of the disc corona. In both cases, the process responsible for the continuum emission is thermal Comptonization.

The conclusion of negligible thermal pair production differs from that of Stern et al. (1995), whose models are pair-dominated at $\gamma = 0.8$. Their models have $\tau \ll 1$ and $kT \sim 511$ keV, which allows them to be pair-dominated at a relatively low compactness. These models can fit the average OSSE spectrum of the radio-quiet Seyfert 1s of Zdziarski et al. (1995) and Gondek et al. (1996). However, we are able to rule out $\tau \ll 1$ by direct fitting to the NGC 4151 spectra, which are of much higher statistical accuracy.

We have also compared our 1991 and 1993 multiwavelength observations with archival $Ginga$ and EXOSAT, GRANAT and OSSE data. It appears that the intrinsic spectrum with $\gamma \approx 0.8$ of 1991 and 1993 belongs to a high, soft state of NGC 4151. The archival data also show a continuum of states limited by a low, hard, state with $\gamma \approx 0.3$ (as found before by YW91 and Y95). The hardening of the $X$-ray spectrum with the decreasing $X$-ray flux results in the spectrum pivoting at a few hundred keV (YW91; Y93). This property allows the $\gamma$-ray spectrum, which breaks at ~100 keV, to vary only to within a factor of a few (as observed by OSSE and GRANAT), while the X-rays vary much more strongly (see Fig. 4). This behaviour can be modelled, for example, as the result of a strongly varying soft (UV) photon flux irradiating the $X\gamma$ source with a weakly varying $X\gamma$ luminosity.

The hardness of the $X$-ray spectrum observed in some states of NGC 4151 by $Ginga$ and EXOSAT is not unique among AGNs, and it is similar to that of, e.g., some Seyfert 2s (Smith & Done 1996). An interesting example is $MCG -5-23-16$. Two $X$-ray spectra from $Ginga$ (Smith & Done 1996) are compared with the OSSE spectrum (Johnson et al. 1994) of that AGN in Fig. 7. The spectral indices are 0.44 and 0.62 (for a fit with a power law that has an exponential cut-off) for the lower and higher $X$-ray states, respectively. This is within the range observed in NGC 4151 (Section 2.4.2). We see that the variable $X$-ray power law pivots around 100 keV. As a consequence, both $Ginga$ spectra can be fitted together with the OSSE spectrum (not simultaneous). Also, the $K\alpha$ line in MCG $-5-23-16$ has the constant line flux in the two different continuum states, as well as having no detectable Compton reflection (Smith & Done 1996), which is similar to some states of NGC 4151 (Section 2.4.2).

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APPENDIX A: OPTICALLY THICK THERMAL COMPTONIZATION

We use the thermal Comptonization model of LZ87 to fit the spectra of NGC 4151. That work uses the Kompaneets equation with a relativistic correction to energy transfer between photons and electrons (equation 22 in LZ87). In the relation between the photon density inside the source and the photon escape rate, LZ87 also take into account reduction at relativistic photon energies of the photon build-up inside the source owing to diffusion (equation 21 in LZ87). The Kompaneets equation is then solved numerically for an assumed distribution of seed photons, $kT$ and $\tau$.

LZ87 use a photon escape probability formalism to obtain the spectra of escaping photons. This implies that the $\tau$ used in the Kompaneets equation corresponds to a source with the assumed escape probability. Thus, that $\tau$ is geometry-dependent, and it approximately equals the radial optical depth in a uniform sphere. A geometry-independent quantity is the spectral index of the asymptotic low-energy spectrum, $\alpha$ (at energies above those of the seed photons). In the model of LZ87, it equals

$$\alpha = \frac{9}{4} \frac{1}{(kT/m_e c^2)^{\gamma}(1 + \tau/3)} \left(1 - \frac{1}{2}\right)$$

(cf. Sunyaev & Titarchuk 1980). Thus, we use the geometry-independent parameters, $\alpha$ and $kT$, as the model parameters.

For a specific geometry, we determine the actual optical depth of a source by a Monte Carlo method. The method is based on that of Górecki & Wilczewski (1984). We have tested it in the range of $\tau$ from 0.5 to 5 against the corresponding results of Pozdnyakov, Sobol’ & Sunyaev (1983) and found excellent agreement.

Fig. A1 shows an example of the (excellent) agreement between the spectra from the Monte Carlo method (squares) and that of LZ87 (dashed curve). The low-energy spectral index is $\alpha = 0.38$, which is imposed for both the solution of the Kompaneets equation and the Monte Carlo spectrum, and $kT = 60$ keV. The optical depth used in the Kompaneets equation is 3.2, whereas the actual $\tau$ of a uniform sphere with a uniform distribution of seed photon sources is 3.0. This discrepancy in $\tau$ has a negligible practical importance as the derived optical depth is only representative for the astrophysical source of an unknown geometry.

The method of LZ87 formally assumes that the Comptonizing plasma is optically thick. We find that $\tau \gtrsim 2$ (for a sphere) is already sufficient for the validity of the method of LZ87. Fig. 6 in Section 3.1 shows a limiting case with $\tau = 1.3$ ($\alpha = 0.80$ and $kT = 88$ keV for the LZ87 solution), when the assumption of the plasma being optically thick starts to become invalid. We see that then the method of LZ87 still gives an excellent description of the Monte Carlo results (at the same $\tau$), but it overestimates the value of $kT$, with the actual value from the simulations of $kT = 61$ keV.

Fig. A1 also compares the Monte Carlo results (for $\tau \sim 3$, when the diffusion approximation applies) with those obtained using the solution of Titarchuk (1994; that solution is also published in TM94 and in a few other papers).
Titarchuk (1994) also uses the Kompaneets equation, but with a set of relativistic corrections different from those in LZ87. We take $kT = 60$ keV and $\alpha = 0.38$ (corresponding to $\tau = 3.1$) in the solution of Titarchuk (1994). We see that the spectrum of Titarchuk (1994) underestimates the actual spectrum in the range $E \sim kT$ by a factor $\sim 2$. Furthermore, that solution give a sharp kink at about 100 keV, which is clearly unphysical.

The kink appears owing to an attempt (equation 3 in TM94) to account for the relativistic high-energy cut-off steeper than that given by the Wien law (analogous to the diffusion-suppression factor of equation 21 in LZ87). For large values of $\alpha$, equation (3) in TM94 gives a suppression with respect to the low-energy formula (equation 2 in TM94). However, the situation reverses at small values of $\alpha$, when the spectrum without the cut-off correction is already below the correct spectrum, and a hump appears in the spectrum above the kink (see Fig. A1). Concluding, the model of Titarchuk (1994) and TM94 may introduce large errors in fitting X-ray data.

Figure A1. Comparison of Comptonization spectra from a spherical plasma cloud with $kT = 60$ keV, and $\tau$ such that the asymptotic low-energy index is $\alpha = 0.38$. Squares represent Monte Carlo results, the solid curve corresponds to the model of Titarchuk (1994) and TM94, and the dashed curve corresponds to the solution of LZ87.