The origin of the correlation between the UV and X-rays in NGC 4151

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ABSTRACT

We propose that the UV/X-ray correlation observed in NGC 4151 by EXOSAT and IUE is due to reemission of the X-ray flux absorbed by cold clouds in the line of sight. This transmission model satisfies the energy balance, provides a good fit to the X-ray and UV data, and predicts no Compton reflection of X-rays (as observed). The correlation can alternatively be explained by reprocessing of X-rays and γ -rays by a cold accretion disk. A specific model in which X-rays and γ -rays are emitted by a dissipative patchy corona and have the spectrum cut off at $\sim 100 \text{ keV}$ (as seen by OSSE) is shown to be energetically possible even if it does not give as satisfactory a fit as the transmission model. However, the model predicts a Compton-reflection spectral component, whose presence remains to be tested by future detectors sensitive above 10 keV.

Key words: accretion, accretion discs — galaxies: individual: NGC 4151 — galaxies: Seyfert — Seyfert: X-rays — ultraviolet: galaxies — X-rays: galaxies

INTRODUCTION AND SUMMARY

Correlation between the UV and X-ray fluxes in radio-quiet AGNs ranges from good to non-existent (e.g., Ulrich 1994). So far, a good correlation was observed in the Seyfert galaxies NGC 4151 (Perola et al. 1986, hereafter P86) and NGC 5548 (Clavel et al. 1992). Here we consider the origin of the correlation in NGC 4151, a nearby Seyfert 1.5 galaxy at the distance of $D \simeq 20$ Mpc.

The correlation in NGC 4151 was observed during two IUE/EXOSAT campaigns in 1983 November 7–19 and 1984 December 16–1985 January 2 (P86). The UV flux at 8.5 eV was proportional to the 2–10 keV X-ray flux corrected for absorption (Section 2). The time delay between the flux variations was less than ~ 2 days. The delay, however, was more tightly constrained to $\lesssim 0.5$ day in 1993 December (Warwick et al. 1996), when the light curves were sampled at time intervals much shorter than in 1983–86.

In the first part of this *Letter*, we present a new model explaining the correlation. We propose that the UV radiation is from reemission of X-rays absorbed by cold matter outside the X-ray source (Section 3). Thus, we identify the matter responsible for the UV emission with that responsible for the observed absorption of X-rays. The column density, $N_{\rm H} \sim 10^{23} {\rm ~cm^{-2}}$, is determined from modeling the X-ray spectra (P86). We show that this model (hereafter referred to as the transmission model) gives an excellent fit to the

UV and X-ray data as well as it satisfies the energy balance. The model implies only residual Compton reflection (Lightman & White 1988) because the absorber is Thomson-thin, $\tau \sim 0.1$, which is in agreement with hard X-ray observations (Maisack & Yaqoob 1991; Yaqoob et al. 1993; Zdziarski, Johnson & Magdziarz 1996, hereafter Z96). The absorbed flux is mostly from the observed 2-10 keV range and thus the model does not depend on the shape of the γ -ray spectrum, which was not observed during the X-ray/UV observations.

From considering the absorber column density, ionization balance, and free-free absorption we determine that the absorber is not uniform but rather made of many dense discrete clouds. The clouds are optically thick to UV radiation and their temperature is $kT \simeq 3$ eV. The obtained cloud parameters are similar to those postulated to exist in the inner regions of AGNs by Guilbert & Rees (1988) and Ferland & Rees (1988).

After presenting the transmission model we reexamine a previously proposed model of reprocessing by an opticallythick accretion disk (hereafter referred to as the reflection model; Section 4). In that model, the correlation is due to the disk irradiated from above by X-rays and γ -rays (hereafter $X-\gamma$) and reemitting the absorbed flux in the UV (Ulrich et al. 1991; Ulrich 1994; Perola & Piro 1994, hereafter PP94).

A number of problems appear in the reflection model. One is the observed absence of a strong spectral component at $\gtrsim 10$ keV expected from Compton reflection of the irra-

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diating X-rays from the optically thick disk (Yaqoob et al. 1993; Z96). [This contrasts the other Seyfert with a UV/X-ray correlation, NGC 5548, which X-ray spectrum does have a prominent Compton-reflection component (Nandra et al. 1991).] Furthermore, the most detailed version of the model, proposed by PP94, requires that in order to satisfy the energy balance the extrapolated X-ray emission has to extend to ~ 4 MeV, which has not been confirmed by recent OSSE measurements (Z96). In that case, the observed large intrinsic dispersion of the 2–10 keV spectral index (P86) implies that the extrapolated power-law flux near ~ 4 MeV (which dominates the absorbed flux for the hard spectrum of NGC 4151) becomes a strongly dispersed function of the 2–10 keV flux, which in turn implies a poor X-ray/UV correlation (see Section 4), contrary to the data.

We show here that most of the above difficulties can be dealt with by choosing a source geometry different from the central optically-thick spherical emission region proposed by PP94. Namely, we propose that the X- γ source forms a dissipative corona above the surface of the disk, as in the model of Seyfert 1's of Haardt & Maraschi (1993) and Haardt, Maraschi & Ghisellini (1994). However, the corona is more patchy than in Seyfert 1's to account for X-ray spectra of NGC 4151 being much harder than those of average Seyfert 1's (Z86). We find that the corona geometry results in a strong reduction of the required X- γ luminosity with respect to the model of PP94. We find that the UV/X- γ energy balance is satisfied even if the incident X- γ spectrum is cut off at ~ 100 keV, as observed by OSSE. This low cutoff energy also reduces the dispersion in the correlation of the total absorbed power with the 2-10 keV flux. However, the model does predict a Compton-reflection spectral component only marginally consistent with hard X-ray observations.

Note that both models are similar in that both postulate absorption of X-rays by some cold medium, which subsequently reprocesses and reemits the absorbed flux as UV photons. The principal difference is that the medium is Thomson-thin in the transmission model whereas it is very Thomson-thick in the reflection model.

2 THE DATA

We have refitted the EXOSAT ME argon data (from 1.2 to 10–15 keV) using a model consisting of a power law, Fe K α line, absorption by a dual neutral absorber (i.e., a product of partial and complete covering, P86), and a constant soft X-ray component modeled as in Z96. We assume an Fe overabundance of 2.6, which is the average value obtained by P86. We find the X-ray energy spectral indices, $\alpha_{\rm X}~(F_E \propto E^{-\alpha_{\rm X}})$, where F_E is the energy flux), are weakly constrained by the argon data alone. Those indices were determined before in the 3.5–25 keV range by P86, who used the ME xenon data extending up to 25 keV in addition to the argon data. The addition of the xenon data resulted in the allowed ranges of $\alpha_{\rm X}$ much narrower than ours. Since the xenon ME data are no longer available we used the ranges of $\alpha_{\rm X}$ as given in P86 (in the range of ~ 0.2–0.7), which we found consistent with the argon data. (We have checked that relaxing this assumption increases the error bars shown on the figures here but it does not affect our qualitative conclusions.)



Figure 1. The correlation between the absorption-corrected EF_E at 5 keV and at 8.5 eV observed during the 1983–1986 campaigns by *EXOSAT* and *IUE*. The vertical error bars on Figs. 1, 2, 3a are for $\Delta\chi^2 = 2.7$, i.e., 90 per cent confidence for one parameter of interest.

Fig. 1 shows the resulting correlation between the absorption-corrected EF_E at 5 keV (of the power-law only) and at 8.5 eV [from *IUE*, dereddened with E(B-V) = 0.05, PP94; Kriss et al. (1995) obtain a similar value of 0.04]. We see the correlation is close to linear at high significance. The values of EF_E in X-rays are similar to those in the UV, which is indeed highly suggestive for the origin of the UV from some form of reprocessing of X-rays.

3 THE TRANSMISSION MODEL

The fits in Section 2 give us the fluxes absorbed by the cold matter in the line of sight, $F_{\rm abs}$. We assume that the absorbing clouds are dense enough for almost complete thermalization of that flux (see below). We determine the temperature of the absorber by requiring that the spectral index in the UV between 8.5 and 7.2 eV equals the average observed value, $\alpha = -0.15$ (Ulrich et al. 1991; PP94). This gives $kT \simeq 3$ eV. Fig. 2 compares the predictions of that model with the data, assuming

$$F_{\rm UV} = fF_{\rm abs} + F_0,\tag{1}$$

where $F_{\rm UV}$ is the integrated UV flux (related to the plotted flux at 8.5 eV by the blackbody formula), $F_0 = 0.05$ keV cm⁻² s⁻¹ is a residual flux, and f = 0.60 takes into account a covering of the X- γ source by the clouds of $< 4\pi$ as well as an efficiency (< 1) of the conversion of the absorbed flux into the blackbody continuum. We see that there is a very good agreement between the data and the model in spite of our rather simplified assumptions (constant T, f, F_0 , pure blackbody UV spectrum). Since f < 1, the model does satisfy the energy balance, i.e., there is more than enough power in the absorbed X-rays to account for the observed UV emission.



Figure 2. Comparison of the prediction of the transmission model with the IUE/EXOSAT data. The crosses give the absorbed flux, $F_{\rm abs}$, obtained from the EXOSAT data, and $EF_E(8.5 \text{ eV})$ is from IUE. The solid line gives $EF_E(8.5 \text{ eV})$ as a function of $F_{\rm abs}$ from the transmission model (see text).

We consider now constraints on the absorbing medium. For simplicity, we assume that all the absorption occurs in a single cloud. From the fits, we obtain the typical column density of a cloud in the partial absorber of $N_{\rm H} \sim 10^{23}$ cm⁻² with the typical covering factor of ~ 0.5. The $N_{\rm H}$ of the complete absorber is a few times less. The dominant thermalization process at 8.5 eV is free-free, which implies that the size of a single cloud, $r_{\rm c}$, is $\leq 10^7$ cm (equivalently $n \geq 10^{16}$ cm⁻³), in order for the free-free optical depth at energies ≤ 10 eV to be > 1 at T and $N_{\rm H}$ as above. At those conditions, collisions alone are sufficient to almost fully ionize hydrogen, and thus there are enough free electrons for free-free absorption.

The average size of the entire absorber, r, can be determined from the blackbody law, $L_{\rm UV}$ (~ 10^{43} erg s⁻¹) = $4\pi\sigma T^4 r^2$, to be ~ 10^{14} cm, which satisfies the limit $r \leq 10^{15}$ cm (for geometry close to spherical) from the relative UV/X-ray time delay (Section 1). The ionization parameter, $L/(nr^2)$, is then ≤ 0.1 , which implies metals are almost neutral, and thus soft X-rays are strongly absorbed in bound-free processes. The parameters of the absorber are similar to those studied by Ferland & Rees (1988; see their Fig. 8) and Guilbert & Rees (1988), for which they find the UV spectrum at ≤ 10 eV is indeed thermalized. Equipartition magnetic fields can confine the clouds with the above parameters (Celotti, Fabian & Rees 1992). The X- γ source has to cover ~ 0.1 of the sky as seen from a typical cloud in order to satisfy the X-ray constraints on soft-photon starvation (Z96). Summarizing, the transmission model both explains the data and appears to be self-consistent.

It appears that accretion of the clouds in the observed absorber alone is insufficient to power the AGN. The total mass in the clouds is independent of their number, and is $\sim f(4\pi/3)N_{\rm H}r^2m_{\rm p} \sim 10^{28}$ g. On the other hand, the mass required to account for $L \sim (3-10) \times 10^{43}$ erg s⁻¹ (assuming a cutoff at ~ 100 keV as observed by OSSE) at an efficiency of 0.1 is ~ (3-10) $\times 10^{27}/\beta_{\rm r}$ g, where $\beta_{\rm r}$ is the radial velocity. Thus, the two masses marginally agree only for highly relativistic radial velocities.

4 THE REFLECTION MODEL

Here we reexamine the reflection model, in which the correlation arises from X- γ irradiating an optically-thick accretion disk (e.g., PP94). The incident X- γ flux is mostly absorbed since the albedo is $A \sim 0.3$ (Z96). The absorbed power is reprocessed and reemitted locally by the disk mostly as UV blackbody radiation, similarly as in the transmission model.

PP94 have developed a detailed model explaining the correlation, in which the X- γ source forms an optically thick central sphere irradiating a surrounding disk. They find that the amplitude of the UV emission at 8.5 eV and the 7.2–8.5 eV spectral index (Ulrich et al. 1991) can be both explained only when the hard power-law emission extends to rather hard γ -rays; e.g., a cutoff above ~ 4 MeV is required for a typical $\alpha \sim 0.5$. (We have reproduced those results using the assumptions of PP94.)

As discussed in Section 1, there are major difficulties with such hard γ -ray emission. First, it has not been seen by the modern γ -ray detectors, OSSE and SIGMA (e.g., Z96; Finoguenov et al. 1995). Although γ -rays were not measured during the EXOSAT/IUE campaign, a UV/X-ray correlation was also seen in 1993 December (see Section 5; Warwick et al. 1996), when the OSSE data showed $kT \simeq 50^{+20}_{-10}$ keV (Z96). Second, α_X varies from 0.2 to 0.7 in the EX-OSAT data (P86). As a result of the dispersion of $\alpha_{\rm X}$, the total fluxes, $F_{X\gamma}$, in the power-law spectra extrapolated to 4 MeV correlate very poorly with the 2–10 keV fluxes. We find that indeed the corresponding reprocessed fluxes are away by factors up to 3 from their best-fit linear correlation with the UV, which invalidates the model (unless the dispersion is compensated for by suitable shapes of the γ -ray spectra, which seems unlikely).

However, it is possible that other source geometries could be more compatible with the data. We study here a model in which the X- γ source forms a patchy corona above the surface of an accretion disk (Haardt, Maraschi & Ghisellini 1994). We assume that all dissipation takes place in the corona (Haardt & Maraschi 1993; Svensson & Zdziarski 1994). Thus, the local power, Q(r), released in the hot corona depends on radius, r, as the disk dissipation rate (Shakura & Sunyaev 1973),

$$Q(r) = \frac{3}{8\pi} \frac{GM\dot{M}}{r^3} \left[1 - \left(\frac{3r_{\rm S}}{r}\right)^{1/2} \right],$$
(2)

where $r_{\rm S} = 2GM/c^2$ is the Schwarzschild radius, M is the black hole mass, and \dot{M} is the mass accretion rate. The power released in the corona is emitted partly outward and partly towards the disk. We assume here that the luminosity

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intercepted by the disk equals R times the luminosity emitted outward (and observed). R can be < 1 due to, e.g., a finite size of the cold disk or an outflow of the hot plasma. On the other hand, the luminosity emitted outward is related to the total observed X- γ flux, $F_{X\gamma}$, by $L_{X\gamma} = 4\pi D^2 F_{X\gamma}$. Then the luminosity absorbed and reemitted thermally by the disk is,

$$L_{\rm UV} = (1 - A)RL_{\rm X\gamma} = 4\pi (1 - A)RD^2 F_{\rm X\gamma},$$
(3)

where $A (\simeq 0.3)$ is the albedo. Energy balance then implies that the luminosity $L_{\rm UV}$ equals the disk emission at the rate,

$$\sigma[T(r)]^4 = Q(r)(1-A)R/(1+R), \tag{4}$$

integrated over the disk surface. This allows us to solve for the constant, \dot{MM} , in equation (2), as well as it shows that the UV spectrum is a standard blackbody disk spectrum (Shakura & Sunyaev 1973) (rather than the singletemperature blackbody spectrum in the transmission model, or the spectrum from irradiation by an optically thick sphere in the model of PP94).

The total observed UV flux is given by,

$$F_{\rm UV} = 2\mu(1-A)RF_{\rm X\gamma},\tag{5}$$

where the factor 2μ accounts for disk emission with a constant specific intensity. Using the blackbody disk spectrum, we can then relate the observed 8.5 eV flux to the total UV flux, $F_{\rm UV}$, as a function of $r_{\rm S}^2\mu$, where $\mu = \cos i$ and i is the disk viewing angle (see PP94). Fig. 3a shows this relation for several values of $r_{\rm S}$ assuming $\mu = 0.42$ [as obtained by HST, Evans et al. (1993); $r_{\rm S}$ for other values of μ scales as $\mu^{-1/2}$]. Fig. 3b shows the corresponding 7.2–8.5 eV spectral indices, compared with the observed values (Ulrich et al. 1991).

The curves in Fig. 3*a* can be compared with the total fluxes, $F_{\rm UV}$, absorbed by the disk and reemitted in the UV as obtained extrapolating the *EXOSAT* power laws to γ -rays in the way observed by OSSE, i.e., for thermal Comptonization at kT = 60 keV (Z96). Z96 obtained the best fit values of $R \sim 0$ –0.3 (at $\mu = 0.42$) based on measuring a Compton reflection component in hard X-ray spectra, with R = 0.5 marginally consistent with the data (see also Maisack & Yaqoob 1991), and we thus use R = 0.5. Note that $R \ll 1$ would not be consistent with the assumption that reprocessing is in the disk. Crosses in Fig. 3*a* give $F_{\rm UV}$ for $R\mu = 0.21$ (corresponding to R = 0.5 and $\mu = 0.42$).

We can now compare predictions of the disk model for various $r_{\rm S}$ with the UV spectral indices and $F_{\rm UV}$ inferred from the *EXOSAT* data. We find first that $r_{\rm S} < 2.4 \times 10^{12}$ cm fit the UV spectral indices, with the upper limit corresponding to $\Delta \chi^2 = 2.7$. The value of $r_{\rm S} = 1.3 \times 10^{12}$ cm provides the best fit to the absorbed fluxes inferred from the X-ray data for $R\mu = 0.21$. The upper limit on $r_{\rm S}$ corresponds to $R\mu = 0.15$. We note that the relative contribution of Compton reflection to the hard X-ray spectra decreases *slower* than $\propto \mu$ (Magdziarz & Zdziarski 1995), and thus the problem of the weakness of Compton reflection together with the presence of reprocessing in NGC 4151 cannot be resolved by postulating $\mu \ll 1$ (Z96).

Note that the fit in Fig. 3a is significantly worse than that for the transmission model (Fig. 2). This is caused by the main contribution to $F_{\rm UV}$ being from ~ 100 keV, relatively far away from the 2–10 keV range, where the linear correlation is observed. Still, the correlation is much closer to



Figure 3. Comparison of the predictions of our reflection model with the data. (a) Crosses give the total UV flux, $F_{\rm UV}$, from reemission of the absorbed X- γ flux as obtained extrapolating the EXOSAT X-ray power laws to γ -rays assuming thermal Comptonization at kT = 60 keV, see text. The curves relate the total $F_{\rm UV}$ to $EF_E(8.5 \,{\rm eV})$, as predicted by the disk spectrum for various Schwarzschild radii, $r_{\rm S}$. (b) Crosses give the UV spectral indices. Curves give the indices predicted by the disk-corona model. We see that the (solid) curve for $r_{\rm S} = 1.3 \times 10^{12}$ cm provides the best description of both the UV fluxes and spectra.

linear than that obtained by extrapolating the X-ray spectra to 4 MeV.

The range of $r_{\rm S}$ obtained above corresponds to $M \lesssim 8 \times 10^6 M_{\odot}$. At the largest M and the source size $\gtrsim 10 r_{\rm S}$, $\Delta t \gtrsim 10^3$ s, compatible with the observed longer variability time scales. (Note that M larger than that given above can be obtained for a Kerr metric.) The range of the maximum disk temperatures is 7–10 eV. Note that the implied range of EF_E at 100 keV is 0.1–0.3 keV cm⁻² s⁻¹, which is much larger than that in 1991–93, when OSSE observed a relatively constant 100 keV flux (Z96).

Summarizing this section, we find that reprocessing by a disk is a viable model for NGC 4151 if the X- γ spectra are cut off at ~ 100 keV. Our conclusion differs from that of PP94, who required that the power-law spectra extend to ~ 4 MeV in order to satisfy the energy balance. The difference is entirely explained by the different geometrical models adopted by PP94 and us. First, our geometry gives $2(1 + \mu)$ times more reprocessed flux (for unit observed X- γ flux). Physically, this is due to a small solid angle subtended by the disk as seen from a point on the surface of the sphere, as well as due to the optically-thick sphere emitting only outside (as opposed to the corona emitting both outside and inside). Second, our model gives the UV spectrum different from that of PP94, with our UV spectrum compatible with the data without the need for γ -ray emission harder than observed.

The main *caveat* for this model is the predicted Compton reflection, with $R\mu \gtrsim 0.15$. Such reflection is only marginally allowed by the X-ray data.

5 OTHER OBSERVATIONS

The two models proposed above explain the UV/X-ray correlation observed in 1983–86. However, the behavior of the UV and X- γ in NGC 4151 changes from one epoch to another. In 1979 May 19–31, $EF_E(8.5 \text{ eV})$ was ~ 0.25 keV cm⁻² s⁻¹ while $EF_E(5 \text{ keV})$ was ~ 0.07–0.12 keV cm⁻² s⁻¹ (Perola et al. 1982). The UV flux is larger than that implied by the specific correlation of Fig. 1. The sampling of the UV flux was too sparse to either establish or rule out a UV/X-ray correlation in that period with an F_0 larger than that in 1983–86.

A correlation with a large F_0 has been in fact observed in 1993 November 30–December 10 (Warwick et al. 1996). The $EF_E(8.5 \text{ eV})$ varied within ~ 0.5–0.6 keV cm⁻² s⁻¹ [using E(B-V) = 0.05, Section 2] together with the 1–2 keV flux (measured by *ROSAT* and *ASCA*). The $EF_E(5 \text{ keV})$ varied in the ~ 0.05–0.25 keV cm⁻² s⁻¹ range, whereas the flux above 50 keV measured simultaneously by OSSE varied only within ±15 per cent.

Preliminary estimates indicate that 1993 December data can be explained by either the transmission or reflection model; discussion is given in Warwick et al. (1996). We only note that a large residual UV flux is required in the transmission model whereas the reflection model may explain most of the constant UV component as due to disk reprocessing of the approximately constant γ -rays.

6 CONCLUSIONS

We have found that the X-ray/UV correlation in NGC 4151 seen by EXOSAT and IUE can be explained by either of two models. In the first one, the UV flux is due to reemission of the X-ray flux absorbed by small, Thomson-thin clouds, which absorption is directly measured in X-rays. The model provides an excellent fit to the data.

In the other model, the X- γ source forms a patchy, dissipative corona above the surface of an accretion disk. The disk reprocesses a fraction of the X- γ flux into the UV, which has been proposed before but for a central X- γ source. The geometry proposed here allows the UV/X- γ energy balance to be satisfied for X- γ spectra cut off at ~ 100 keV, as observed by OSSE.

The reflection model requires spectral hardening above 10 keV, owing to the presence of Compton reflection. This can be tested by X- γ observations including coverage of the 10–50 keV range (e.g., by *XTE*), where the relative contribution from Compton reflection peaks. The two models make

different predictions regarding the specific UV-X- γ variability, and thus can be tested by coordinated multiwavelength observations.

Note that the transmission model produces the UV within the X-ray absorber so that the expected absorption in the UV is different than that produced in the reflection model, where the UV and X-rays both are affected by the same absorber (as proposed by Warwick, Smith & Done 1995). The recent data from the Hopkins Ultraviolet Telescope appear to rule out the latter possibility (Kriss et al. 1995), thus favouring the transmission model.

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