Models of optical/UV continuum in AGN: constraints from the NGC 5548 monitoring campaign

Z. Loska and B. Czerny

Nicolaus Copernicus Astronomical Center, Bartycka 18, 00-716 Warsaw, Poland

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ABSTRACT

We analyse the data from the International Ultraviolet Explorer (IUE) observational campaign on the Seyfert galaxy NGC 5548 in the context of 10 phenomenological models. On the basis of the optical/UV data, as well as of constraints from the X-ray observations, we can favour one model of the nucleus: an accretion disc with an inner radius cut-off surrounded by a hot corona. The second acceptable model for optical/UV data is a distribution of optically thin clouds. However, X-ray constraints which were crucial in the analysis of disc-type models could not be applied; further development of this model is necessary.

Key words: accretion, accretion discs – galaxies: active – galaxies: individual: NGC 5548 – galaxies: Seyfert – X-rays: galaxies.

1 INTRODUCTION

The nearby spiral galaxy NGC 5548 (z = 0.0174) is one of the best laboratories for testing active galactic nuclei (AGN) models (Rokaki, Collin-Souffrin & Magnan 1993). The nucleus is bright (absolute visual magnitude −24.3), the interstellar extinction in this direction is exceptionally low (hydrogen column $N_H \sim 1.65 \times 10^{20}$; Nandra et al. 1991) and the nucleus is strongly variable in the optical, the UV and the X-ray bands. Extensive monitoring of that galaxy is reported in a number of papers devoted to optical (Peterson et al. 1991; Peterson et al. 1992; Peterson et al. 1994), UV (Clavel et al. 1991), and simultaneous Ginga and IUE (Clavel et al. 1992) campaigns. It was also one of the few AGN detected in the usually unobserved EUV band (Marshall, Fruscione & Carone 1995).

The overall IR–UV spectrum (e.g. Ward et al. 1987) and X-ray spectrum (e.g. Nandra & Pounds 1994, Done et al. 1995) of the nucleus of NGC 5548 is fairly typical for a Seyfert 1 galaxy although the spectroscopic classification identifies it usually as Seyfert 1.5.

The amplitude of the variability of NGC 5548 is considerable at every wavelength from optical to hard X-rays.

In the optical band a significant fraction of the luminosity is thought to be due to the contribution of starlight (e.g. Kotilainen & Ward 1994). The flux measured at 5100 Å varied by a factor of 2 during the four years of the campaign (1988–92). The UV flux monitored during 1988–89 varied by almost a factor of 3 at 1350 Å.

As the continuum variations in all three UV bands and the optical band were simultaneous (down to a measurable delay of a few days: Clavel et al. 1991), most of the optical/UV variability can be accounted for by the reprocessing of hard X-rays, as suggested by Malkan (1991) and Collin-Souffrin (1991) (see also Krolik et al. 1991, Clavel et al. 1992 and Rokaki et al. 1993). A dominant role for reprocessing is also consistent with Ginga data (Nandra & Pounds 1994) which clearly show the presence of the reflection component superimposed on a typical hard X-ray power law (energy index $\sim 0.9$), with reflected fraction of the order of the usual 2π. Recent ASCA data (Mushotzky et al. 1995) support this conclusion as they show the Kα line profile consistent with a disc around a Kerr black hole inclined $\sim 15°$–$38°$ with respect to an observer. As the iron line is broad (FWHM $> 35,000$ km s$^{-1}$) most of the emission comes from the region smaller than $\sim 36$ Schwarzschild radii. In most epochs the X-ray flux above 2 keV is strongly variable (a factor of 2 between separate observations; Nandra & Pounds 1994) but without systematic trends in the change of the energy index. In soft X-rays the variability pattern is more complex due to the presence of soft X-ray excess and the warm absorber (see Nandra et al. 1993 and Done et al. 1995 for ROSAT observations).

However, occasionally strong enhancements of the big bump component are seen (in the UV in 1984 May: Clavel et al. 1992; in soft X-rays in 1992 December/1993 January: Done et al. 1995) that are unrelated to hard X-ray luminosity and indicate direct liberation of gravitational energy in the form of optically thick emission in these periods.
Multiwavelength studies put constraints on any models of the nucleus by determining or limiting the connections and delays between spectral bands. As for the continuum, both optical and UV spectra follow X-ray flux behaviour (with the exceptions mentioned above) with a delay of less than 6 d (Clavel et al. 1992). In the case of UV this delay is most probably smaller than 2 d, which suggests that the size of the UV emitting region is of the order of $5 \times 10^{16}$ cm. Large-amplitude changes in soft X-ray emission happen over 2 d and large-amplitude variations of hard X-rays also require time-scales of the order of 2 d (e.g. Done et al. 1995).

The available data was mostly used to study the structure of the broad-line region (BLR) (e.g. Done & Krolik 1996) as in that case the delays are easily measurable.

A model of the continuum emission of NGC 5548 was elaborated by Rokaki et al. (1993). The model consisted of an inner disc emitting X-rays (modelled as a sphere of a constant radius and variable luminosity), an outer standard disc and an optically thin surrounding medium. The outer disc was irradiated by X-rays either directly or by photons scattered by the thin medium. Such a model adequately represented the data from the IUE campaign but formal fits were not presented so a quantitative analysis was impossible.

In this paper we discuss a number of simple phenomenological models and we fit them to the data from the same observational campaign. We show that for a black hole mass of $6 \times 10^7$ $M_\odot$ (as estimated on the basis of X-ray reprocessing, UV and X-ray variability and emission lines) only two of these models are actually acceptable if the optical/UV data requirements are supplemented by the constraints from (non-simultaneous) X-ray data. The first of these two models is a non-stationary accretion disc with variable accretion rate and a variable inner radius cut-off. Part of the gravitational energy available below the cut-off radius is liberated in the form of X-rays in the hot corona surrounding the disc and part of it is thermalized owing to absorption by the disc. The second model is the distribution of the (identical) optically thin clouds the emission of which in the optical/UV band can be approximated as free–free emission.

The content of the paper is following. Models are described in Section 2. In Section 3 we describe the method of analysis of the data including the problem of the starlight contribution and the contribution of Balmer continuum and blended Fe II lines at 2670 Å. The results are given in Section 4. Section 5 contains the discussion of the results. Conclusions are given in Section 6.

## 2 MODELS OF OPTICAL/UV CONTINUUM

We introduce a number of viable models describing the extension of the optically thick disc-like part of the flow and the geometry of the source of X-ray radiation. As there are no detailed theoretical predictions about the formation of these two phases of accreting gas we introduce phenomenological parameters but with a physically sound interpretation. All models considered here do not contain more than two free time-dependent parameters as we fit only a time sequence of four frequency points. However, models may contain additional parameters that do not vary with time, such as the mass of the central black hole etc., and they do not reduce noticeably the number of the degrees of freedom.

The first three models are based on the assumption that the only variable component is the X-ray flux incident upon a stationary accretion disc. The next five models are based on variations in the accretion rate at the innermost part of the disc which in turn may cause a change in irradiation. As a single optical/UV spectrum consists of only four points we approximate the local thermal emission of the disc by a blackbody with the effective temperature distribution calculated including the viscous dissipation (determined by accretion rate) and the irradiation flux appropriate for the adopted geometry (taking albedo equal to 0.9). We assume a non-rotating black hole, i.e. Schwarzschild geometry.

The next model is the simplest version of emission by optically thin clouds. Finally, we also fit a single power-law model for a better discussion of the quality of the data.

### 2.1 Stationary accretion disc and a point-like X-ray source

This model consists of a standard stationary Keplerian disc around a massive black hole of the mass $M$ and accretion rate $\dot{M}$, and a point-like source of X-ray radiation localized on the disc symmetry axis and characterized by the luminosity $L_X$ and distance from the disc plane $H_X$. Such a geometry was frequently suggested and it was used in a number of papers devoted to modelling AGN emission (e.g. Ross & Fabian 1993, Życki & Czerny 1994). It may, for example, approximate the situation where hard X-ray emission is produced by shocks which may accompany the formation of the jet (e.g. Henri & Pelletier 1991, Liang & Li 1995). Since it was suggested that the variable irradiation is mostly responsible for the variable optical/UV emission (Clavel et al. 1991, Rokaki et al. 1993) we assume that $M$ is constant while $L_X$ and $H_X$ vary. The local effective temperature in the disc is calculated by taking into account the stationary viscous flux and the thermalized X-ray flux. Computing the last term we assume that the albedo for X-rays is equal to 0.9, as determined by Lightman & White (1988) (see also Życki et al. 1994), as the reflection component observed in hard X-ray data indicates the presence of neutral gas (Nandra et al. 1991).

### 2.2 Stationary accretion disc with geometrically thick optically thin inner part

As the standard accretion disc model with $zP$ viscosity (Shakura & Sunyaev 1973) is thermally unstable in the inner parts the inner disc may become optically thin and hot. Such a flow was studied in a number of papers (Shapiro, Lightman & Eardley 1976; Wandell & Liang 1991; Kusunose & Zdziarski 1994). The physics behind this is complex but a simplified geometrical model can be used: the transition radius $R_X$ defines the cut-off radius for the optically thick standard disc (e.g. Siemiginowska & Czerny 1989). The inner part of the disc is replaced by an inner optically thin disc of luminosity $L_X$. The shape of the inner disc is approximated by a sphere of radius $R_X$. We do not require that the gravitational energy available below $R_X$ is equal to $L_X$ in order to account for possible magnetic storage of the energy in the optically thin region. The sphere irradiates the outer optically thick parts of the disc. A similar model was actually...
fitted to the light curve of NGC 5548 by Rokaki et al. (1993). The difference between their model and the one presented here is in their assumption of constant $R_c$ ($3 \times 10^{17}$ cm) and the presence of additional irradiation of the disc due to an extended hot medium. In our model we assume a constant accretion rate in the outer parts of the disc but allow for variations of both $L_x$ and $R_c$. It again implies some storage of the energy by the inner disc.

2.3 Stationary accretion disc irradiated by a hot corona

A number of papers were devoted to the scenario in which most of the energy is dissipated in the disc corona instead of in the disc interior (e.g. Liang & Price 1977, Paczyński 1978, Zycki, Collin-Souffrin & Czerny 1995). We roughly model such a situation assuming that the standard stationary accretion disc of a given $M$ and $M$ is irradiated by the corona, effectively producing the local flux

$$F_{\text{cor}} = A (r/3r_g)^{-\delta},$$

where both $A$ and the index $\beta$ were allowed to vary. To express the model parameters more conveniently we use the bolometric luminosity of the corona rather than the coefficient $A$ {both are easily related by the integration over radius, i.e. $L_x = 18\pi 4r_g^2[(r_{\text{cut/3r_g}})^{2-\beta} - 1]/(2-\beta)$ for $\beta$ not equal to 2}. In this model the strength of the corona is unrelated to the accretion rate.

2.4 Non-stationary accretion disc with advection-dominated innermost part

The time-scale of the UV variability of the order of a few days is actually consistent with the viscous time-scales of the inner few Schwarzschild radii if the viscosity parameter is high (see, e.g., Siemiginowska & Czerny 1989). Therefore we study the hypothesis that the observed spectral changes are actually driven by the variations in the accretion rate. In this model we assume that the innermost part of the disc may become optically thin. If such optically thin flow is dominated by advection (e.g. Narayan & Yi 1995) only a small fraction of energy released in this part of the flow would emerge in the form of X-rays and irradiate the optically thick parts. Since this X-ray emission can then be an arbitrarily low fraction of the available gravitational energy we neglect the irradiation, as the data are not good enough to introduce another free parameter.

Therefore, in this model we simply assume that the standard disc extends down to a certain cut-off radius $R_c$ and the part of the disc below does not contribute to UV radiation flux.

2.5 Non-stationary accretion disc with inner radius cut-off and a point-like X-ray source

If the gravitational energy cannot be stored efficiently by the magnetic field then model 2.1 of the point-like source is incorrect. Therefore we consider another model in which an accretion disc extends only down to a certain cut-off radius $R_c$. The remaining available energy not dissipated in the disc is now dissipated in the point-like source. Such a model is motivated, for example, by suggested ejection of plasmoids at the expense of the gravitational energy of the inner part of the disc (e.g. Liang & Li 1995). We assume that the X-ray source is located on the symmetry axis at a distance $R_c$. We allow now for variable accretion rate $M$ in the disc as the cut-off radius may (in fact, should) depend on it. Therefore the model again has two variable parameters.

2.6 Non-stationary accretion disc with geometrically thick optically thin inner part

If the energy cannot be stored as efficiently by the inner hot part of the disc as it can by that in model 2.2 then the luminosity of this part has to be matched by the available gravitational energy below $R_c$. In close analogy with model 2.2 we now choose the disc accretion rate $M$ and the cut-off radius $R_c$ filled by the spherical inner disc as our variable parameters; the bolometric luminosity of the sphere and the effect of irradiation of the disc by its X-ray emission are uniquely determined by these two values. The model is also complementary to model 2.4 as this time we neglect the advection losses and allow for the irradiation of the optically thick parts of the disc.

2.7 Non-stationary accretion disc with inner radius cut-off and scattered X-ray radiation

This model differs with respect to the previous two in the geometry of the irradiation by X-ray. This time we assume that the luminosity is released in the centre and redirected towards the disc by scattering in an optically thin, hot medium. Effectively, we just make the assumption that the incident luminosity is inversely proportional to the square of the distance. Similar dependence on a distance was adopted in the next model but this time the cut-off radius enters the luminosity only through the total X-ray luminosity whilst in the corona model 2.8 the cut-off radius would enter also through the normalization.

2.8 Non-stationary accretion disc with inner radius cut-off irradiated by the corona

This model differs from model 2.3 as now we consider the specific example of the dependence of the corona parameter on the accretion rate in the disc. We now assume that the standard disc extends not to the marginally stable orbit but only to a certain cut-off radius $R_c$, as in model 2.4. The gravitational energy below this radius is now exchanged into X-ray photons and redirected towards the disc by the corona or dissipated by the corona according to the law

$$F_{\text{cor}} = A (r/R_c)^{-\beta},$$

where $A$ is determined by the available bolometric luminosity below $R_c$. As fits of the model 2.3 to the data favoured the value $\beta$ of about 2, we fixed $\beta$ in the present model mostly at the value 2. Therefore our model has again only two independent parameters.

2.9 Free-free emitting clouds

As the existence of accretion discs in the centres of active nuclei is questioned (see, e.g., Barvainis 1993) and optically thick clouds (e.g. Guilbert & Rees, 1988, Lightman & White 1988, Sivron & Tsuruta 1993) or optically thin clouds (Anto-
nucci & Barvainsi 1988; Ferland, Korista & Peterson 1990) reprocessing hard X-ray radiation are suggested to be responsible for emission in the optical/UV/soft X-ray band, we consider a cloud model as well. We assume that clouds are optically thin for absorption (nevertheless they can be optically thick for scattering) and their radiation can be well approximated as a bremsstrahlung emission at a single temperature $T$. Such a spectrum has two parameters: the temperature $T$ and normalization $V$,

$$F_v = V g_{\text{a}}(v, T) T^{-\frac{1}{2}} \exp(-h v/kT),$$

(3)

where the Gaunt factor $g_{\text{a}}(v, T)$ is taken from Gronenschild & Meuw (1978). The normalization $V$ is proportional to the emitting volume and to the square of the electron density.

We introduce this model due to its recent popularity but it is necessary to realize that real cloud spectra would be dominated by strong emission lines, particularly for temperatures lower than ~10$^4$ K (e.g. Krolik & Kriss 1995, Collin-Souffrin et al. 1996).

2.10 Power-law model

In order to check how important is the correct determination of the spectrum curvature in the successful models we also fit a simple power law to the same data, with the slope and the normalization being free parameters of this formal model. Such a pure power-law model has no direct physical interpretation, although a contribution of a power-law component to the optical data of unspecified origin has been broadly discussed (e.g. Loska & Czerny 1990). Also, in the course of analysis of the BLR contribution to the continuum an assumption was made that the continuum can be approximated as a power law so the fit serves as a test of this hypothesis.

3 METHOD OF ANALYSIS

3.1 Observational data

3.1.1 Observational campaign

As the contribution of starlight might be considerable in the optical band and its influence strongly decreases with the studied frequency we concentrated on the analysis of the continuum when the UV data are available. The IUE observations of NGC 5548 covered the period 1988 December–1989 August and the fluxes at 350, 1480 and 2670 Å (Spectral Image Processing System: SIPS) were taken from Clavel et al. (1991), and at 5100 Å from Peterson et al. (1992). We favoured the 5100-Å value over the 4870-Å flux from Peterson et al. (1991), as the second quantity is contaminated by the H$\beta$ emission and therefore less accurate, as argued by Peterson et al. (1992). The optical measurements were carefully corrected by observers for the aperture effects and reduced to a standard (4) set taken with the aperture 5.0 × 7.5 arcsec$^2$.

3.1.2 Starlight problem

The flux measured at 5100 Å is thought to be contaminated by starlight from the host galaxy. The original optical data measured using different instruments and apertures were corrected in such a way that only the starlight present in the small-aperture data 5.0 × 7.5 arcsec$^2$ remained. As the method did not rely on any specific spectral shape of the starlight the adopted procedure was actually independent of the nature of the extended emission.

However, in order to model the intrinsic variability of the nucleus all the starlight contribution had to be removed from the data. For that purpose we assumed that the shape of the starlight in NGC 5548 was well represented by the emission from the nucleus of M31, as shown by Wamsteker et al. (1990). We adopted the relative starlight contribution at 5100 Å in the standard aperture equal to 3.4 × 10$^{-15}$ erg s$^{-1}$ cm$^{-2}$ after Romanishin et al. (1995). Having such normalization, we subtracted the starlight from all four frequency points although at 2670 and 1840 Å, and clearly at 1350 Å, its contribution is actually negligible (never higher than 2 per cent).

3.1.3 Balmer continuum and blended Fe II lines

The flux at 2670 Å is additionally contaminated by contribution from the BLR. Peterson et al. (1991) estimate this contribution as 20 per cent of the measured flux. However, the variations of the nuclear emission are followed by variations of the Balmer continuum and blended Fe II emission with possibly smaller amplitude and a delay of order of a few days. Maoz et al. (1993) therefore made a much more detailed analysis of the BLR continuum. They showed that the typical delay of the emission due to the blended Fe lines was of order of 10 d and they determined the total luminosity of this component in the band 2160–4130 Å in each data set. We therefore calculate the correction to the 2670-Å flux as a mean flux in this spectral band and we adopt 20 per cent of this value as an error, as suggested by the authors. There may be a contribution of the BLR to the 1840 Å at a level of up to 10 per cent but this effect is smaller than the correction at 2670 Å and not studied so carefully so we did not include it while correcting the data.

3.2 Fitting procedure

We fit the models to the data calculating the value of $\chi^2$ at every time point separately, so

$$\chi^2 = \sum_{i=1}^{4} \frac{(y_i^\text{obs} - y_i(a_1, a_2))^2}{\sigma_i^2},$$

(4)

where $y_i^\text{obs}$ is the observed value and $y_i(a_1, a_2)$ is calculated from any of our two-parameter models. Errors $\sigma_i$ of the measurements at 1350 and 1840 Å are taken directly from table 2 (SIPS) of Clavel et al. (1991), while errors at 2670 Å were calculated assuming the errors of the subtracted BLR continuum equal to 20 per cent of the determined flux and the error of subtracted starlight at 5100 Å was taken equal to the error of the total flux at minimum.

We search for the minimum with respect to the parameters $a_1$ and $a_2$ at every time point using the procedure AMOEBA given by Press et al. (1989, chapter 10.4). In order to accept or to reject the model we calculate the global value of the reduced $\chi^2$ for a given model (i.e. we sum the contributions to $\chi^2$ from all four frequencies in all time points and divide by the number of d.o.f., including those connected with the global parameters) while the fits at every time point
give us the value of the model parameters as functions of time.

4 RESULTS

4.1 Fits of theoretical models

The last two models, namely the free-free emission (model 2.9) and a power law (model 2.10) do not include any global model parameters apart from the two parameters varying with time, so their analysis is the simplest.

The variations of the energy index with the luminosity clearly show the well-known trend in Seyfert spectra, i.e. the spectrum is harder when the source is brighter. However, the curvature is the essential property of the spectrum so the fit of model 2.10 to the data is poor (see Fig. 1 and Table 1). Any model giving the $\chi^2$/d.o.f. above ~1.52 can be rejected at the 99.9 per cent confidence level for the number of the degrees of freedom between 90 and 92 in models presented. It means that the approximation of the continuum to a power law used to analyse the BLR contribution is not very accurate. This may also mean that the continuum obtained by subtracting BLR contribution estimated on the basis of a power-law shape of the continuum may also contain some systematic errors.

A better fit is provided by the free-free isothermal model, Fig. 2. The variable temperature allows it to account for the variable spectral curvature. The total $\chi^2$ is only marginally above 1 so the model is accurate. The model contains a strong correlation between the temperature and the normalization factor. It means that either the volume or the density (or both) increase when the temperature increases, although the relative change in temperature is more than a factor of 2 larger. This trend is not in contradiction to the expected behaviour. If the time-scale for expansion of the clouds under variable irradiation is long we expect no variations of the volume measure. If this time-scale is short and the cloud adjusts itself to a constant ionization parameter $\xi$ to preserve its thermal stability (e.g. Collin-Souffrin et al. 1996) the density may indeed decrease with an increase of irradiation giving in effect an increase in the measure of emission $V$ as defined in the model (i.e. proportional to the product of the emitting volume and the square of the electron density). However, the result presented should not be treated as a satisfactory test of the cloud model, since the temperatures appropriate for the overall curvature of the

![Figure 1. Energy index $\alpha$ versus the normalization constant $L_\alpha$ for a power-law fit (model 2.10). Error bars represent 90 per cent confidence level.](image)

| Model | Mass/$M_\odot$ | $\beta$ | $\chi^2$/dof |
|-------|----------------|--------|--------------|
| 2.1   | $1 \times 10^7$ | 0.01   | 1.05         |
|       | $\alpha$       | 0.1    | 0.87         |
|       | $\alpha$       | 0.5    | 0.99         |
|       | $6 \times 10^7$| 0.01   | 0.87         |
|       | $1 \times 10^8$| 0.005  | 0.93         |
|       | $5 \times 10^8$| 0.001  | 0.67         |
| 2.2   | $1 \times 10^7$| 0.01   | 1.03         |
|       | $\alpha$       | 0.1    | 1.03         |
|       | $\alpha$       | 0.5    | 1.03         |
|       | $6 \times 10^7$| 0.1    | 1.01         |
|       | $1 \times 10^8$| 0.005  | 1.02         |
|       | $5 \times 10^8$| 0.001  | 2.69         |
| 2.3   | $1 \times 10^7$| 0.01   | 2.66         |
|       | $\alpha$       | 0.1    | 2.86         |
|       | $\alpha$       | 0.5    | 4.22         |
|       | $6 \times 10^7$| 0.001  | 2.16         |
|       | $5 \times 10^8$| 0.005  | 1.75         |
| 2.9   | ---             | ---    | 1.15         |
| 2.10  | ---             | ---    | 2.68         |

Table 1. The values of $\chi^2$ per 1 d.o.f. Models are numbered according to the corresponding paragraphs. Adopted values of global parameters (mass of the black hole in solar masses and accretion rate in Eddington units of the index $\beta$), if appropriate, are given in columns 2 and 3.
spectrum are not much higher than $10^7$ K and the analytic free-free formula is not an adequate description of the spectrum actually dominated by line emission.

All the remaining models contain some global model parameters. We fix the value of the mass of the central black hole on the basis of available information. However, as the adopted value can be questioned, we show the major trends in the dependence on global parameters in Section 4.3. Other parameters ($\beta$ in model 2.8 and $m$ in models 2.1, 2.2 and 2.3) are chosen arbitrarily but the dependence of the fits on these parameters were tested.

The mass of the central massive black hole seems to be known relatively well. Its value most probably lies between $5 \times 10^7$ and $6 \times 10^7 M_\odot$ (Rokaki et al. 1993), and X-ray observations confirm the inclination angle $\sim 20^\circ-30^\circ$ used to derive these limits.

X-ray reprocessing also supports this value directly. The delay of the UV emission with respect to the X-ray data by not more than two days indicates that the reprocessing region is of order of $5 \times 10^{15}$ cm. The same region should be responsible for the formation of the broad K$\alpha$ Fe line. The width of the line larger than 35 000 km s$^{-1}$ corresponds to the Keplerian orbit below $\sim 36 r_g$. The two dimensions are in mutual agreement for the mass of the central black hole of about $6 \times 10^7 M_\odot$.

Direct modelling of the optical/UV data with an accretion disc gave an upper limit for the value of the black hole of $5 \times 10^7 M_\odot$ (Loska, Czerny & Szczepańska 1993). The estimates of the mass of the black hole based on the kinematics of the BLR lead to the value of about $10^8 M_\odot$ (e.g. Wanders et al. 1995) or somewhat smaller (Done & Krolik 1996).

Therefore in our basic analysis we adopt the value of the mass of the black hole of $6 \times 10^7 M_\odot$ obtained from the most accurate estimates and consistent with all available constraints.

For this value of the central black hole we found that only the models 2.3 and 2.7 do not fit the data. All other models represent well the behaviour of the optical/UV flux. Fits of model 2.3 with larger and smaller values of $m$ does not improve the fit considerably as the model only weakly depends on $m$. Model 2.7 does not include additional global parameters, apart from the mass of the black hole.

This result is not surprising, as all the models were designed in such way as to have enough flexibility. However, the constraints on the model parameters lead to very interesting results.

Of the three stationary models, the first two are clearly acceptable, which means that we cannot differentiate between the point-like X-ray source and an extended source of X-ray emission. However, it is interesting to note that in both cases involved the X-ray luminosity is considerably larger (by a factor of 2 to 17) than the luminosity viscously liberated in a disc. It is generally not surprising, as the variable irradiation has to account for the observed amplitude of the flux changes.

The second property the two models have in common is the relatively large height of the X-ray source above the disc plane; the radius of the optically thin sphere or the height of the point-like source above the disc plane is of order of $(30-60)r_g$. Such a constraint was by no means imposed on the models.

Among the non-stationary models, only model 2.7 is not acceptable. The remaining models provide good fits to the data. Again, all of them show very similar behaviour. The variability is driven by the change in accretion rate (by up to a factor of 3) of about a value of the order of 0.2. The cut-off radii vary less and in all cases are antidependent with the accretion rate; the effect is strongest in model 2.7 and almost invisible in model 2.4.

One of these models (model 2.4) does not include any irradiation by X-rays. The model fits the data well. For the value of the mass of the central black hole adopted in these calculations the cut-off radius is practically uncorrelated with the accretion rate. Nevertheless, its presence is the essential part of the model. Fits of the same model with the cut-off radius fixed at the mean value ($\sim 16.5r_g$) are much worse ($\chi^2=3.00$/d.o.f.). It might mean that the transition from the optically thin to the optically thick solution in the innermost part of the disc is not determined by the accretion rate but by some other external parameter, e.g. magnetic field. Although not intuitive, such a possibility cannot be easily excluded.

If the irradiation is allowed the variations of accretion rate are of smaller amplitude than in model 2.4, as they are enhanced by absorbed X-rays. Although in all models there is a weak anticorrelation of the cut-off radius and the accretion rate, the liberated X-ray luminosity is directly correlated with the accretion rate although the dependence is somewhat weaker than linear.

In these models the height or the size of the X-ray source is about a factor of 2 smaller than in models with constant accretion rate, so the match consistent with K$\alpha$ constraints is much easier to achieve.

Models 2.3 and 2.7 are unable to fit the data as they do not produce enough of the spectrum curvature in the UV band. They represent well NGC 5548 when it is bright but are unable to model the spectrum when the object is fainter, and the maximum of the spectrum is clearly seen on the log($\nu F_\nu$) versus log($\nu$) diagram. However, this conclusion is
Figure 3. Stationary models. Model 2.1: upper panel; model 2.2: middle panel; and model 2.3: lower panel. The left side of the diagram shows the dependence of the X-ray bolometric luminosity of the model \( L_x \) measured in \( 10^{44} \) erg s\(^{-1} \) versus the flux at 1350 Å in units \( 10^{-14} \) erg s\(^{-1} \) cm\(^{-2} \) Å\(^{-1} \) as measured directly (full dots) and as derived from the best-fitting model (open circles). The right side of the diagram shows the dependence of the height of the point-like source \( H_x \) in \( r_g \) units, the size of the optically thin part of the disc \( R_x \) in \( r_g \) and index \( \beta \), for models 2.1, 2.2 and 2.3 correspondingly, as functions of the X-ray bolometric luminosity, this time measured in units of the accretion disc viscous luminosity. Error bars represent 90 per cent confidence level.

It is interesting to note that the anomalously high continuum measurements at optical wavelengths on JD 2447546 discussed by Peterson et al. (1991) is reproduced by models 2.3, 2.7, 2.8, 2.9 and 2.10, but not by the others.

4.2 Constraints from the X-ray observations

There was no continuous coverage by any X-ray satellite during the \textit{IUE} campaign analysed in detail in this paper. However, shorter simultaneous observations were carried out with the \textit{Ginga} satellite (Clavel et al. 1992). Also, recent high-quality \textit{ASCA} observations put constraints on the models. These additional requirements can be used to reduce the number of models allowed by the optical/UV data alone.

The simplest constraint comes from the mean bolometric X-ray luminosity. Although its value is not known accurately due to the uncertainty of the high-energy extension of the hard X-ray power law a reasonable estimate gives a value up to \( 5.5 \times 10^{44} \) erg s\(^{-1} \) (Done et al. 1995) when the source is bright (for an adopted value of the mass of the central black hole this luminosity translates into \( m=0.08 \)). During the campaign analysed in this paper the source was generally dimmer. All the models containing the irradiation should return an X-ray luminosity of order of or below this limit. This condition is satisfied by models 2.1, 2.5 and 2.8 (among the models with acceptable \( \chi^2 \)) but not by models 2.2 (for \( r_h=0.1 \)) and 2.6 (see Table 1). Allowing for lower \( m \) in model 2.2, we still find an increase in the luminosity. Larger value of accretion rate leads to acceptable luminosities but at the same time it increases the cut-off radii to unacceptable values larger than \( 36 r_g \) (see below).

The constraint does not apply to model 2.4 as in this case the energy flux available for X-ray production is mostly advected below the horizon of the black hole.

The result of the X-ray monitoring was the proportionality of the X-ray luminosity and 1350-Å flux, with flattening when the 1350-Å flux was above \( 5 \times 10^{-14} \) erg s\(^{-1} \) cm\(^{-2} \) Å\(^{-1} \). Therefore in Figs 3 and 4 we plot the X-ray luminosity derived from models versus 1350-Å flux. We see that the scatter on the diagrams showing stationary models is much smaller than in the observational data in fig. 4 of Clavel et al.
Figure 4. Non-stationary models: panels from the top to the bottom show models 2.4, 2.5, 2.6, 2.7 and 2.8. The left side of the diagram shows the dependence of the X-ray bolometric luminosity of the model $L_x$ measured in $10^{44}$ erg s$^{-1}$ versus the flux at 1350 Å in units $10^{-44}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ as measured directly (full dots) and as derived from the best-fitting model (open circles). In model 2.4 the X-ray energy shown is the total energy available below the cut-off radius; most of this energy is advected and only an arbitrarily low fraction of it might eventually emerge in the form of X-rays. The right side of the diagram shows the dependence of the cut-off radius of the disc $R_c$ in $r_g$ as function of the accretion rate measured in Eddington units. Error bars represent 90 per cent confidence level.

(1992). We can also use the formula from Clavel et al. (1992) to predict the range of the 2–10 keV flux expected from the observed range of the 1350-Å flux. If we additionally use the bolometric correction of Done et al. (1995) we estimate the total X-ray luminosity range to be $(1.4–5.1) \times 10^{44}$ erg s$^{-1}$. X-ray luminosities derived for the models 2.1, 2.5 and 2.8 cover just this range.

The strength of the observed Kα line requires that approximately half of the X-ray flux is reprocessed by the disc and the other half reaches an observer without interaction with the disc. This requirement is approximately satisfied by all models in which irradiation is present as the optically thin part of the disc is never significantly larger than the height, or extension, of the X-ray source so almost half of the flux can be intercepted.

ASCA observations in turn constrain the geometry of the models. According to these data (Mushotzky et al. 1995) the Kα iron line has FWHM larger than 35 000 which corresponds to Keplerian orbits below $\sim 36r_g$. This has two consequences.

The first limit imposed on the models is that the optically thick part of the disc extends considerably below $36r_g$. This condition is satisfied by models 2.1, 2.4, 2.5 and 2.8 as well as by some other models rejected on the grounds of their high X-ray luminosity.

The requirement that most of the lines form at about $36r_g$ and below also puts constraints on the location of the X-ray source. In the case of a point-like source illuminating the plane most of the reprocessing takes place in a region with a radius of about $\sqrt{3}r_g$ so this height should be of order of $25r_g$ or somewhat smaller. This requirement is not satisfied by the stationary model 2.1, as the fitted X-ray source height in this model covers the range of $(35–70)r_g$.

In the case of a model with inner radius cut-off $R_c$ and X-ray source placed at height $R_c$ (model 2.5) half of the reprocessing takes place below the radius $\sqrt{3}R_c$, which limits $R_c$ to values smaller than $\sim 14r_g$. This requirement is not satisfied since values as large as $30r_g$ are reached.

In model 2.4 we assumed that the energy released below...
the cut-off radius is mostly advected under the horizon. However, the comparison of the observed X-ray luminosity with the available one (see Fig. 4) shows that only \( \sim 50 \) per cent of the energy should be advected and the remaining \( \sim 50 \) per cent is necessary to explain the observed direct X-ray emission and the reflected component. Such a considerable irradiation flux modifies the distribution of the effective temperature, contrary to the initial assumption. Therefore the model 2.4, although satisfactory from the point of view of the optical/UV data, either does not produce X-rays (contrary to observations) or is not self-consistent (influence of X-rays cannot be neglected).

Model 2.8 is therefore the only disc model (for a black hole mass equal to \( 6 \times 10^7 \, M_\odot \)) fully in agreement with the available observations. The other acceptable description of the optical/UV data gives the free-free model (model 2.9); in this case the constraints from the X-ray observations are difficult to apply as it would require the inclusion of additional parameters into the model representing the geometry of the cloud distribution.

### 4.3 Dependence on global parameters

We explored the dependence on global parameters by fitting models for a few values of the global parameters involved.

The dependence of the results on the assumed mass of the central black hole is essential in all non-stationary disc models. Since we explicitly limited the accretion rate to remain below the Eddington value all non-stationary models give unacceptable fits if the mass of the black hole is \( 1 \times 10^7 \, M_\odot \). If the black hole is very massive (\( 5 \times 10^8 \, M_\odot \)) the temperature of the disc becomes too low to account for the X-ray emission, although models tend to settle themselves on to the solutions without effective cut-off (i.e. \( R_c = 3r_s \)) in order to ease this problem.

The value of the mass of the black hole of about \( 1 \times 10^7 \, M_\odot \) is optimal for all non-stationary models, independent of geometry. The values of \( \chi^2 \) for all models are smaller than or comparable to the values obtained for \( 6 \times 10^7 \, M_\odot \), even models 2.3 and 2.7 are acceptable. What is more, the models ruled out on the basis of having reprocessing regions that are too extended (models 2.1 and 2.5) are perfectly consistent with X-ray data, as the cut-off radius decreases with an increase in the mass of the black hole. Also the X-ray bolometric luminosity is smaller and the predicted values agree to within \( \sim 50 \) per cent (apart from model 2.7, as before) with expected values (see Section 4.2).

This trend is related to the drop of the disc temperature with an increase of the mass of the central black hole and there is no need for a large cut-off radius in order to explain the observed low temperature of the thermal emission. However, it is interesting to note that again the best model is model 2.8, this time purely on the basis of having the lowest reduced \( \chi^2 \).

As the stationary models have an energy source of unspecified nature we did not introduce any a priori constraint on the luminosity. As a result, most models fit the data for all values of the mass of the central black hole. They depend very weakly on the accretion rate of an underlying accretion disc as the X-ray luminosity strongly dominates disc luminosity. Models for low values of the mass of the black hole marginally satisfy the constraints imposed by the total X-ray luminosity (the brightest models exceed the estimated limit only by 40 per cent). Models for high mass are too bright by up to a factor of 4. Therefore again the central mass at about \( 6 \times 10^7 \, M_\odot \) is strongly favoured.

The dependence of stationary models on the adopted value of the accretion rate of the disc is very weak, as the X-ray luminosity strongly dominates, and the contribution of the radiation flux due to the disc viscosity is negligible in comparison with the thermalized X-ray flux.

### 4.4 Properties of the best models

Constraints from the IUE observational campaign and from the available X-ray data reduced the acceptable models of the nucleus of the Seyfert galaxy NGC 5548 to just two models: a non-stationary accretion disc with a corona (model 2.8) and free-free emitting clouds (model 2.9). We cannot favour either of the two models as they are less specific than other models as regards the geometry and no additional constraints are available for them.

Both models fit the optical/UV data well, as the actual spectra predicted by the models in this frequency band are almost identical. We can see this in Fig. 5, which shows the plot of the two model spectra in one of the highest luminosity states (date 7622) and one of the lowest states (date 7738). The high-state spectrum is almost a power law while the low-state spectrum has significant curvature (actually, it shows a maximum in the \( \nu F_\nu \) diagram). Both models follow these changes very well. Both models in the low state are somewhat underluminous at 2670 Å, which probably indicates systematic error in the subtraction of the BLR contribution.

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**Figure 5.** Observed optical/UV spectrum of the nucleus when the source was faint (date 7738 - upper panel) and when it was bright (date 7622 - lower panel) are shown with dots. Best fits to the data by the corona model 2.8 is marked as a continuous line and the best fit of the free–free model 2.9 is marked with a dotted line. \( F_\lambda \) is given in units \( 10^{-14} \) erg s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\) and \( \lambda \) in Å.
The accretion rate (measured in units of the bolometric luminosity. This means that the strength of the emission as a function of the cut-off radius measured in units of the radius of the marginally stable orbit equal to 3r_g.

Some of the properties of model 2.8 are shown in Fig. 4. The cut-off radius varies between 0.05 and 0.14. The cut-off radius varies between 6r_g and 13r_g, and it is clearly anticorrelated with the X-ray bolometric luminosity. This means that the strength of the corona decreases with increasing accretion rate. Such a trend is in agreement with a period of even stronger UV time-scales, as functions of the wavelength, were carefully estimated by Siemiginowska & Czerny (1989).

5 DISCUSSION

As was already concluded in the first paper on the monitoring campaign of the Seyfert galaxy NGC 5548 (Clavel et al. 1991), the optical/UV emission is dominated most of the time by the reprocessing of the X-ray radiation and further observations confirmed this conclusion. Our models also support this trend.

The analysis presented in this paper favours one among the disc-type models of the nucleus: the disc/corona model.

We also found the cloud model to be acceptable and at present we are unable to differentiate between them. The comparison is, however, unfair, since acceptable disc models had to satisfy several very strong constraints based on X-ray data whilst optically thin clouds were introduced as purely parametric models without reliable description of their spectra and without a global scenario which would allow us to use X-ray constraints on this model as well.

The disc/corona model depends on additional global parameters, including the mass of the central black hole. We adopt the value of 6 \times 10^7 M_\odot (for arguments, see Section 4.1). Lower \chi^2 values for all models, including the disc/corona model, were obtained for a somewhat larger value (1 \times 10^7 M_\odot). However, an attempt to derive the value of the mass of the black hole directly from fits will introduce a large error.

Other disc-type models were ruled out by the fact that models had to satisfy two opposite requirements: (i) the emission region had to have low temperature in order to explain the roll-over of the spectrum in the UV band when the object is faint – for a fixed mass, it was achieved by an appropriately large cut-off radius; (ii) the X-ray reflection component has to form close to the black hole so that the cut-off radius has to be small enough to allow the disc to be present close to the black hole. As the disc temperature for a given value of the gravitational radius drops with an increase of the mass of the black hole those conflicting requirements are easy to satisfy when the black hole is more massive. In any case, the disc emission, particularly when the nucleus is faint, does not extend far into the EUV spectral region and is not expected to be seen in soft X-rays.

As the disc/corona model is non-stationary, it poses a question as to whether or not any changes of the accretion rate are possible on such a short time-scale. In order to estimate this we have to realize that the change in the accretion rate at the innermost part of the disc does not require the actual redistribution of the mass in the disc but it may happen on a thermal time-scale, as a transition from one state to another. As the estimates of the time-scales of disc/corona systems are not available we may use just the thermal time-scales of the standard disc based on the viscosity as described by Shakura & Sunyaev (1973). These time-scales, as functions of the wavelength, were carefully estimated by Siemiginowska & Czerny (1989).

To account for the temporary brightening in the UV or the X-ray contribution of the two possibilities, and actually even more models are acceptable if the mass of the central black hole is allowed to be somewhat higher.

Therefore, the problem lies clearly in the too-small dynamical range of the studied spectra. However, the solution of the problem is not easy.

The similarity of the two model spectra when fitted to the optical/UV data clearly shows that it is very difficult to differentiate between the two models. Careful reduction of the data, and removal of both the starlight and the BLR contribution are essential, but not enough to favour either of the two possibilities, and actually even more models are acceptable if the source was bright (but not during that campaign analysed in this paper). To account for such a phenomenon it would be necessary to allow for some viscous dissipation within clouds. However, no specific models of such a clumpy disc are available at present.

The similarity of the two model spectra when fitted to the optical/UV data clearly shows that it is very difficult to differentiate between the two models. Careful reduction of the data, and removal of both the starlight and the BLR contribution are essential, but not enough to favour either of the two possibilities, and actually even more models are acceptable. Careful reduction of the data, and removal of both the starlight and the BLR contribution are essential, but not enough to favour either of the two possibilities, and actually even more models are acceptable if the mass of the central black hole is allowed to be somewhat higher.

Therefore, the problem lies clearly in the too-small dynamical range of the studied spectra. However, the solution of the problem is not easy.

It is relatively simple to include an additional point at \sim 8000 \AA, as the entire spectra are in principle available although their reduction is by no means simple.

Extension of the monitoring from the optical to the soft...
X-ray bands would in principle help significantly but it would make the problem of modelling very complex. Neither optically thin clouds nor disc/corona model spectra can be represented by the simple models considered in this paper (see Collin-Souffrin et al. 1996 for clouds and Zycki et al. 1994 for disc reprocessing). Reliable models are not available yet for the soft X-ray band. However, as soon as acceptable models are proposed such broader fits may be strongly constraining.

More direct use can be made from hard X-ray band monitoring if the data are accurate enough to show the variations in the reflected component. The comparison with such data would not necessarily require much more sophisticated models than currently described. Particularly interesting data would be collected when the source is rather faint, since such observations might determine whether the innermost part of the disc actually undergoes a structural change or whether the accretion rate is temporarily reduced. However such monitoring is beyond the present possibilities.

6 CONCLUSIONS

On the basis of the analysis of the IUE observational campaign of the Seyfert galaxy NGC 5548 and the constraints from the X-ray observations we show that the nuclear emission can be fitted by a model of a non-stationary accretion disc with a corona. Simple analytic free–free formulae representing the emission of the distribution of clouds that are optically thin for absorption gives an acceptable description of the optical/UV data alone. There is no possibility of distinguishing between these two models on the basis of the present data, as it is not clear how to imply the constraints from the X-ray data in the case of a cloud model. Any further progress can only be made if the research is extended either towards careful studies, both observational and theoretical, of the spectral features such as emission lines and edges, or towards broadening of the spectral range towards soft X-rays and/or hard X-rays.

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