MODELING THE X-RAY–OPTICAL CORRELATIONS IN NGC 3516

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ABSTRACT

We test the “reprocessing paradigm” of optical–UV active galactic nucleus (AGN) variability, according to which the variations in this wavelength range are driven by a variable X-ray component, by detailed modeling of the correlated X-ray–optical (3590 and 5510 Å) variability of the recent multiwavelength campaign of NGC 3516. To this end we produce model optical light curves by convolving the observed X-ray flux with the response function of an infinite, thin accretion disk, illuminated by a pointlike X-ray source located at a given height $h_{\text{X}}$ above the compact object (the lamppost model). We also produce the ionized X-ray reflection and Fe Kα line spectra that result from the reprocessing of the same X-rays on the disk surface. Then we compare the properties of the model light curves (amplitude, morphology, lags) as well as those of the Fe Kα line profiles to those observed. Our calculations improve on those of similar past treatments by including the effects of an X-ray–heated ionized layer in hydrostatic equilibrium on its surface, which greatly affects its X-ray timing and spectral properties. The results of our calculations do not provide a clear-cut picture that would either support or refute the reprocessing paradigm: despite the large ($\approx 50\%$) amplitude excursions of the X-ray flux, the model optical light curves exhibit variability amplitudes of only $3\%$–$4\%$ and vary in synchrony in the two bands, in agreement with observations. However, the model light curves, when viewed in detail, do not have a direct correspondence to those observed. Furthermore, while the observed intraband synchrony generally points toward smaller values for the black hole mass ($M = 10^7 M_\odot$), the X-ray Fe Kα line, X-ray reflection, and optical–UV spectra seem to favor larger mass values ($M = 10^8 M_\odot$). Generally, no combination of the model parameters seems to produce agreement with the ensemble of the constraints imposed by optical/UV/X-ray spectral and timing observations; we are thus led to believe that the simplest version of the lamppost model geometry is inconsistent with the NGC 3516 observations.

Subject headings: accretion, accretion disks — galaxies: active — galaxies: individual (NGC 3516) — galaxies: Seyfert — ultraviolet: galaxies — X-rays: galaxies

On-line material: color figures

1. INTRODUCTION

A great deal of effort and observing time have been expended in the past decade or so in a systematic effort to “map” the central regions of active galactic nuclei (AGNs). Because the relevant sizes are too small to image with current technology, the attempted “mapping” has been effected through the time reverberation technique, i.e., the monitoring of the system in response to fluctuations in luminosity across the electromagnetic spectrum and the comparison of the relative amplitudes and lags between different wavelengths and models.

While the original reverberation effort was aimed at estimating the size of the broad-line region by measuring the lags between variations in the ionizing continuum and the broad emission lines (see Netzer & Peterson 1997 for a review), it was quickly realized that the same data could also be used to test models of the continuum emission itself by measuring the lags between variations in the UV and optical flux. The AGN optical–UV (O–UV) continuum is generally dominated by a broad quasi-thermal component, the so-called big blue bump (BBB), thought to be due to—and modeled as—the emission of a geometrically thin, optically thick accretion disk, radiating in blackbody form the locally dissipated accretion kinetic energy (Malkan & Sargent 1982; Malkan 1983; Laor & Netzer 1989; Sun & Malkan 1989). Thus, monitoring the O–UV continuum variability and the corresponding interband lags places constraints on the models of such accretion disks.

It became apparent early on in this extensive mapping effort that the interband lags between optical and UV wavelengths were far shorter than those expected by most modes of information propagation in a thin accretion disk (the lags of the earlier campaigns were generally shorter than the sampling rates). This situation prompted the suggestion that the correlated O–UV continuum variability is due entirely to reprocessing of the more variable X-ray component by the geometrically thin accretion disk responsible for the emission associated with the BBB feature (Krolik et al. 1991). This suggestion appeared to also fit nicely with the evidence of X-ray reflection by cold matter in AGNs (Pounds et al. 1990) and the presence of relativistically broadened Fe Kα lines (see, e.g., Tanaka et al. 1995; see also a recent review by Fabian et al. 2000).

Thus, a “picture” of the innermost regions of accreting black holes began to emerge, consisting of a geometrically thin, optically thick accretion disk radiating away the dissipated kinetic energy in blackbody form, supplemented by an X-ray source located at a height $h_{\text{X}}$ of a few Schwarzschild radii above the disk (or modeled as a spherical source occupying the inner part of the disk). The X-ray source is powered by dissipating a fraction of the accretion luminosity in the region above the disk largely devoid of matter, the energy being transferred there by some means, most likely magnetic fields. The disk’s soft (O–UV) photons were then thought to be the seed photons that, in interactions with the electrons of the hot corona, produce the observed
X-rays, which are in turn reprocessed by the disk to provide the X-ray reflection “hump,” the Fe Kα line, as well as the observed rapid, interband variability between the optical and UV wavelengths.

While fits to the observed X-ray spectra within the general framework of this arrangement seem to be in good agreement with observations, as is well known, spectra generally provide information about column densities and optical depths rather than densities and lengths, which are the quantities needed to confirm the actual geometry of the X-ray–O–UV emission. Verification of the precise geometrical arrangement requires the “mapping” of this geometry through timing observations, as discussed above. Such a (so-called) reverberation mapping requires a sufficiently high data sampling rate, set by the light crossing time from the X-ray source to the reprocessing disk. For a source size roughly a few Schwarzschild radii of a $10^8 M_\odot$ black hole, this timescale (assuming that the source is located several Schwarzschild radii above the disk) is of the order of $10^3$–$10^4$ s. At the same time, the monitoring campaign has to be of sufficiently long duration to sample a large enough number of peaks and troughs to produce a reliable interband cross-correlation.

There have been to date two monitoring campaigns specifically planned to comply with these criteria, namely, those of NGC 7469 (Nandra et al. 1998, 2000) and of NGC 3516 (Edelson et al. 2000). Earlier coordinated multiwavelength observations, while forming a rather extended database (see Nandra et al. 1998 for a summary), were deemed of inadequate sampling rate to provide conclusive results. The results of the NGC 7469 campaign (Nandra et al. 1998) were puzzling in that they indicated no clear correlation between the X-ray variations and those of UV emission, while the flux in both bands exhibited 50% variations in amplitude. At the same time there were clearly detected lags between the UV (1315 Å) and the optical (6962 Å) emission of the order of 1–2 days (Collier et al. 1998). Revisiting these observations, Nandra et al. (2000) have indicated that a softening of the X-ray spectrum with increasing UV flux underestimated the soft X-ray emission. Taking this fact into consideration to correct for the X-ray luminosity, they showed that the longer (~10 day) variations in the UV and X-ray bands were in fact “in sync” with each other, thus providing a resolution to the lack of X-ray/UV–correlated variability. However, the X-rays exhibited, in addition, strong variations on timescales of $\sim 10^4$ s, which had no obvious counterparts in the UV or optical light curves. The NGC 3516 campaign (Edelson et al. 2000) monitored this object in the optical with the Hubble Space Telescope and in the X-ray with RXTE and ASCA for about 3 days with an unprecedented sampling rate. Aiming to detect even the shortest possible reprocessing events, X-ray fluxes and optical spectra were obtained roughly every 200 s, which is roughly the light crossing time across the inner accretion disk of an $M \approx 10^7 M_\odot$ black hole.

Motivated by these results of the NGC 7469 (Nandra et al. 1998) campaign, Berkley, Kazanas, & Ozik (2000, hereafter BKO) examined in detail these observations in the framework of the “disk-reprocessing model”: they produced simulated O–UV light curves using the observed X-ray light curves as input in a geometric arrangement of a point X-ray source at a given distance above the plane of the disk, as thought to be the situation in AGNs. Their conclusions were that for any reasonable estimate of the black hole mass ($10^6$–$10^9 M_\odot$), both the UV (1315 Å) and the optical (6962 Å) continuum emission should follow closely that of the X-rays. In fact, the imprint of the short-time ($t \approx 10^4$ s) X-ray variability was always present in the model-reprocessed emission, with almost undetectable (~0.1 day) lags between UV and optical variations, as measured by the cross-correlation function (CCF) of the simulated light curves in these bands, in disagreement with the findings of Collier et al. (1998). However, they also found that if the reprocessing was driven by a component varying like the UV rather than the X-ray emission (i.e., if it contained no high-frequency fluctuations), then the reprocessed-model optical emission did lag that of the UV by about a day, in rough agreement with Collier et al. (1998), provided that the X-ray source was located at a height of $\sim 3 \times 10^{14}$ cm above the disk plane.

In the present paper we present an analysis of the campaign results of NGC 3516 (Edelson et al. 2000) similar to that of NGC 7469 given in BKO. However, the present analysis is more complete in several respects: (1) The albedo of the illuminated disk is computed (rather than assumed to be small) using the analysis of Nayakshin, Kazanas, & Kallman (2000, hereafter NKK), which takes into account the effects of an ionized “skin” on the surface of the disk induced by the action of X-rays. (2) The effect of the presence of the black hole, more precisely the absence of reprocessing in a region of size $R \lesssim 3 R_g$ underneath the X-ray source, is taken into account. (3) The calculation of the simulated light curves includes a steady component, associated with the intrinsic O–UV emission by the geometrically thin accretion disk, of flux consistent with observations. The main effect of this component is to reduce the variability amplitude. (4) We compute “standard” accretion disk O–UV continuum spectra for the values of the mass and accretion rate obtained from the best fits of the model light curves, which we then compare to observations. (5) The present treatment includes also models of the O–UV and X-ray reflection spectra (with particular emphasis in the Fe Kα lines), which are compared to observations in order to further constrain the model parameters.

Edelson et al. (2000) concluded that the absence of lags between the two optical bands requires the source size to be less than 0.3 lt-day and that this limit is in contradiction with the absence of correspondence between the X-rays and the optical variations, which require a size larger than 2.8 lt-days. Our conclusions are slightly different. We tentatively conclude that there is some correspondence between the X-ray and the optical light curves consistent with the observed optical intraband synchrony, provided that the reprocessing region is larger than about 0.5 lt-day, with certain restrictions imposed by the X-ray–optical lags, however, which we discuss in the text.

Our paper is structured as follows: Section 2 contains a description of the physics involved in the reprocessing of X-rays by a thin disk in hydrostatic equilibrium and also the method for the approximate computation of the X-ray albedo for different X-ray energies under these circumstances. Using the results of the albedo computation, § 3 presents the response functions of the reflected X-rays at two different energies, in order to exhibit the X-ray energy dependence of this effect. In § 4 simulated O–UV light curves, due to reprocessing of the X-rays observed in NGC 3516, are produced for the wavelengths used in the monitor-
ing campaign; their CCFs, as well as those of the X-rays, are computed and compared to those observed. In § 5 we exhibit model O–UV continuum spectra for different values of our system parameters, which we compare to those observed. We also compute the associated X-ray reflection spectra, with particular emphasis in the X-ray reflection and Fe Kα line features, which are compared to those observed. Finally, in § 6 the results are summarized and conclusions are drawn.

2. DISK X-RAY ILLUMINATION AND ALBEDO

The presence of Fe Kα lines and continuum reflection features in the AGN spectra consistent with X-ray reprocessing by neutral matter lead to the belief that the corresponding albedo is that of neutral matter, i.e., \( \alpha \approx 0.1–0.2 \) (see, e.g., Magdziarz & Zdziarski 1995) and that it is thus entirely justifiable to assume this to be its correct value. However, the recent calculations of NKK indicate that the formation of an ionized skin on the surface of an X-ray-irradiated disk can greatly influence both the albedo and the reflected spectra. In particular, when the skin is completely ionized, the spectra may appear to result from reflection by neutral-like matter because the skin itself does not leave any atomic physics imprints on the spectra, with the Compton reflection “hump” and the \( \approx 6.4 \text{ keV} \) Fe Kα line then being formed in the underlying cold, neutral matter. In other words, the fact that one often sees neutral-like reflection and Fe lines in Seyfert I galaxies does not necessarily mean that the reflector is neutral and \( \alpha \ll 1 \). In fact, results of NKK show that the completely ionized skin can yield albedo reaching very high values, such that \( \alpha \approx 0.1–0.2 \) (see, e.g., Nayakshin & Kallman 2001) and that it is thus entirely justifiable to assume this to be its correct value. These modifications allow us to treat the optically thick situations and also arbitrary incidence angles.

2.2. Approximate Radiation Transfer

We assume that the illuminated gas consists of two layers, of which the top one is completely ionized, while the bottom one is neutral. We can then follow the methods described in Sobolev (1975), developed for the treatment of radiation transfer in the atmospheres of planets. In this approach, Compton scattering is assumed to be monochromatic (justifiable here since the photon energies we consider are much smaller than \( m_e c^2 \) and the skin temperature is only roughly a few keV). The cold, neutral medium of the bottom layer is ascribed an albedo, \( \alpha_c \), appropriate to neutral matter (\( \alpha_c = 0.2 \)). Following the derivation given in Sobolev (1975, pp. 153–170), especially his chapter 8.6, one can easily derive an approximate expression for the distribution of the radiation field at any depth within a skin of a given Thomson depth \( \tau_s \). This local radiation field determines the Compton temperature and the angle-integrated intensity of the radiation, which are needed in steps 2 and 4 of the iterative procedure of the calculation of \( \tau_s \) described above.

The same procedure can be also used for the approximate calculation of the energy dependence of the reflected X-ray intensity by using an albedo for the bottom, neutral layer, which is energy dependent. Because we know from our earlier, exact calculations (see NKK) that the temperature of this layer is always sufficiently low so that the gas is weakly ionized, we can simply use the albedo of the neutral matter, given, for example, by Magdziarz & Zdziarski (1995). The reflected X-ray flux at an energy \( E \) is then given by equation (8.100) of Sobolev (1975, with his \( x_1 = 0 \) because we assume that the scattering is isotropic), with the albedo \( \alpha = \alpha_c(E) \) as given by Magdziarz & Zdziarski (1995), and the notation changed appropriately to ours (e.g., \( \tau_s \equiv \tau_s \), etc.). Clearly, this approach is not accurate for sharp spectral features, such as the Fe Kα line, or for high photon energies, i.e., \( E \gtrsim 50 \text{ keV} \) or so, but it is nonetheless adequate for our purposes (see § 3).

2.3. The Albedo

Using the radiative transfer approach described in § 2.2, it is easy to show that the albedo due to the Compton scatterings in the skin is given by

\[
\alpha_{\text{skin}} = 1 - \frac{2 + 3\xi}{4 + 3\tau_s} - \frac{2 - 3\xi}{4 + 3\tau_s} e^{-\omega\xi},
\]

where \( \omega \) is the incident angle for the X-rays. Instead of this, we now use the following iterative procedure: (1) Assume an initial value for the Thomson depth of the skin and calculate the radiation field within the skin with the approximate methods discussed in Sobolev (1975) and described in some detail in § 2.2. (2) Find the gas pressure at the bottom of the skin (the point at which \( P_{\text{gas}} = P_s \); see Nayakshin & Kallman 2001). (3) Determine the geometrical location of the bottom of the skin, \( z_s \). (4) Integrate the hydrostatic balance equation from the bottom up to obtain a new value for the “skin” Thomson depth. (5) Repeat the above steps until the procedure converges. This iterative calculation is in fact similar to the iterative scheme that one uses to solve the problem with “exact” numerical methods (see, e.g., NKK). However, the difference is that here we do not compute the ionization structure of the skin (it is assumed to be completely ionized) and hence can perform the transfer of radiation analytically, reducing the computation time from hours to seconds. We will report details of this approximation in a future publication. These modifications allow us to treat the optically thick situations and also arbitrary incidence angles.
where \( \zeta \) is the cosine of the incidence angle, while \( \tau_0 \) is the total Thomson depth of the skin. This expression assumes that all the X-rays incident on the cold material below the ionized skin are absorbed. In reality, 10\%–20\% are reflected (see Magdziarz & Zdziarski 1995), and thus we approximate this situation by writing

\[
\mathcal{A}_s = \mathcal{A}_{s0} + \mathcal{A}_\zeta/1 + \mathcal{A}_\zeta, \tag{3}
\]

where \( \mathcal{A}_\zeta \) is the integrated albedo of the cold material, which we assume to have the value \( \mathcal{A}_\zeta = 0.2 \). The above approximate expression has the correct behavior for both optically thin (i.e., \( \tau_0 \ll 1 \), when \( \mathcal{A}_\zeta \simeq \mathcal{A}_{s0} + \mathcal{A}_\zeta \)) and thick limits (\( \mathcal{A}_\zeta \simeq \mathcal{A}_{s0} \)) and will suffice for our present study.

3. THE X-RAY REFLECTION RESPONSE

With an approximate expression for the reflected X-ray intensity at hand, we can now discuss the response of the X-rays reflected (rather than reprocessed) by the disk as a function of photon energy. To simplify the treatment, we will consider the response at only two photon energies, namely, \( E = 1 \) and 20 keV. The lower value is representative of the behavior of soft X-rays that are largely absorbed by the neutral reflector (but may be reflected if \( \tau_0 \gtrsim 1 \)), whereas the higher one is representative of the behavior of hard photons that are mostly reflected rather than absorbed. It is of interest to examine whether such different behavior would result in effects between these two bands that could be observed in the time domain. Even though no such analysis has been done for the multiwavelength campaign data of NGC 3516 that we are discussing here, we point out that these timing correlations within the X-ray band itself are an important property of the model, and future observations should be planned so as to extract these correlations in addition to those of the O–UV band with the X-rays.

The geometry of the source considered here is identical to that discussed in BKO: a pointlike X-ray source located at a height \( h_X \) above the accretion disk and, in particular, above the compact object (i.e., the lamppost model). To present a more precise treatment than BKO, we also consider that the reprocessing surface does not extend to the foot of the vertical from the X-ray source onto the disk plane, but only to 3 Schwarzschild radii, \( R_g \). The presence of the black hole, or rather the absence of the reprocessing disk at radii \( r \leq 3R_g \), is of some significance for the response function, especially when \( h_X \lesssim 3R_g \); under these conditions both the minimum lag associated with X-ray reprocessing off the accretion disk and the fraction of the disk-reprocessed X-ray luminosity are significantly different from the case such that no such hole is present. Finally, as in BKO, the observer is considered to be at a position of latitude \( \theta \) above the disk.

Considering the slightly different X-ray source geometries, for example, that of a spherical source of radius \( h_X \), this source should not make much difference to our results. What is of interest in the type of models we study is the general form of the response function of the configuration. A spherical geometry is still expected to have a response with a rising piece of duration \( \approx h_X/c \) (see, e.g., Fig. 1) and a decaying piece very similar to that of the response function of the point source we present here, since the latter is solely geometric, owing to reprocessing of the X-rays by the parts of the disk with \( R \gg h_X \), for which the X-ray appears as a point source.

As shown in BKO, the response function of an infinite plane to an X-ray source at a height \( h_X \) in the direction of the observer (at latitude \( \theta \)), as a function of the time lag \( \tau \) and the radial distance \( R \) from the black hole, is

\[
A(R, \tau) = \begin{cases} 
2R/\sqrt{(\tau - \tau_0)(\tau - \tau_1)} & \text{if } \tau_0 < \tau < \tau_1, \\
0 & \text{otherwise}
\end{cases},
\tag{4}
\]

where \( \tau_1 = D_f/c \) and \( \tau_2 = D_f/c \) are the leading and trailing lags, respectively, at which the ellipses of constant lag (the intersection of paraboloids of constant lag with the disk plane) intersect the circle of a given constant radius (constant X-ray flux). The quantities \( D_f \) and \( D_f \) are given by the expressions

\[
D_f = \sqrt{R^2 + h_X^2} - R \cos \theta + h_X \sin \theta, \tag{5}
\]

\[
D_f = \sqrt{R^2 + h_X^2} + R \cos \theta + h_X \sin \theta. \tag{6}
\]

The reflected X-ray flux, \( F_{XR} \), at a given radius \( R \) depends on the local angle-specific albedo \( \mathcal{A}(E, \theta) \), which, as discussed above, is a function of both the X-ray energy \( E \) and the observer latitude angle \( \theta \). The expression for \( F_{XR} \) is

\[
F_{XR}(E, t) = \frac{L_X(t) \mathcal{A}(E)}{4\pi h_X^2 + R^2} \left( \frac{h_X}{h_X^2 + R^2} \right)^{1/2}, \tag{7}
\]

where \( L_X(t) \) is the luminosity of the X-ray source, which is a function of time. Then, the reflected X-ray luminosity as a function of time, \( L_{XR}(E, t) \), is obtained by integrating the reflected X-ray flux over all lags \( \tau \) and the entire area of the disk. Because of the energy dependence of the albedo, the above quantity depends on the energy of the X-ray photons. Thus,

\[
L_{XR}(E, t) = \int_0^\infty dt \mathcal{A}(R, \tau) F_{XR}(E, t - \tau). \tag{8}
\]

The presence of a minimum disk radius at \( R = 3R_g \) affects the lower limit, \( \tau_0 \), of the time integration in the above equation, which is given by the maximum value of \( D_f(R)/c \) and \( D_f(R = 3R_g)/c \). The effects of the absence of the disk at \( R \leq 3R_g \) are taken into account by considering the proper lower limit and that the integral is zero when \( \tau_0 \geq \tau_0 \). As in BKO, the time and lags are measured here in units of \( h_X/c \).

In order to assess the effects of the different parameters associated with the calculation of the albedo and the disk–X-ray source geometry on the X-ray reflection by the disk, we present its response, i.e., the flux as a function of time resulting from a narrow—in time—pulse of X-rays for a variety of combinations of these parameters. Because the albedo is in addition a function of the X-ray photon energy, we also consider in each case the disk response at two different photon energies, namely, \( E = 1 \) and 20 keV.

The form of the X-ray pulse assumed is that of a Gaussian of unit area, i.e., \( L_X(t) = \exp[-(t - \tau_0)^2/\tau_1^2]/(2\pi\tau_1)^{1/2} \). The pulse width \( \tau_1 \) is a free parameter taking (in units of \( h_X/c \)) the value \( \tau_1 = 0.3 \). The other parameters used are the ratio of the X-ray to disk luminosities, \( \eta_X \), the latitude angle of the observer, \( \theta \), and the height, \( h_X \), of the X-ray source above the disk plane (in Schwarzschild radii). While the mass \( M \) of the black hole does not figure into the geometry of X-ray scattering, it is implicitly involved in the computation of the albedo because it determines the absolute value of the X-ray flux on the disk surface, which in turn deter-
mines its temperature. In all the runs presented in this section, the black hole mass was held constant at the value $M = 10^9 M_\odot$, while the value of $M$ was kept at $M = 0.003$ in units of the Eddington value, yielding a luminosity in general agreement with that of NGC 3516.

Figure 1 presents the response function of a nearly face-on disk ($\theta = 85^\circ$) of $\eta_X = 3$ for three different values of the X-ray source height $h_\times = 10, 3, 1$ (in descending order in the figure) and for two different X-ray photon energies $E = 20$ keV (solid curves) and $E = 1$ keV (dashed curves), along with the input impulse of width $\tau_1 = 0.3$. The figure exhibits clearly the strong dependence of the albedo on the photon energy. Also apparent is the effect of decreasing the X-ray source height $h_\times$ on both the response amplitude and lag at which the response peaks. This effect is due to the absence of reprocessing matter at $R < 3R_g$. Because the disk albedo at photon energy $E = 20$ keV is almost independent of the incidence-reflection geometry and structure of the ionized skin on the disk surface (see upper panel of Fig. 7 of NKK), the response curves overlap at large values of the time (lag). This is clearly not the case with the lower energy photons ($E = 1$ keV), for which the shape of the response changes significantly with $h_\times$ because of the dependence of the value of $\tau_1$ on this parameter.

The difference in response between the X-ray photons of different energies suggests that the presence of the cold disk in the vicinity of the X-ray source would modify the spectrum of the observed radiation, in the sense that the ratio of soft to hard photons received by the observer at infinity will be smaller than that produced by the source because of the larger fraction of soft photons absorbed by the disk. This produces the well-known "reflection" component (Basko, Sunyaev, & Titarchuk 1974; Lightman & White 1988; Magdziarz & Zdziarski 1995), which has apparently been observed in AGNs (Nandra & Pounds 1994). However, in addition to the "hardening" of the (time-integrated) spectrum due to the reflected component, the time delay information is also preserved in the signal: because the fraction of photons that reach the observer after reflection increases with energy (for photons with energies $E_X \lesssim 40$ keV; it decreases after that because of downscattering of the photon energy), the response function of this geometric arrangement should be broader the higher the photon energy. This should also lead to a broader autocorrelation function with photon energy and possibly to hard lags (of the order $\sim h_\times/c$) in the cross spectrum of the observed hard and soft photon light curves, even though the CCFs of the same bands peaks at zero lag.

Figure 2 exhibits the effects of changing the ratio $\eta_X = L_X/L_d$ of the X-ray, $L_X$, to the disk, $L_d$, luminosities. These runs were produced assuming a constant value for the X-ray source height $h_\times = 10$ above the disk and an observer latitude $\theta = 85^\circ$. As in Figure 1, the dashed and solid curves correspond to photon energies of 1 and 20 keV, respectively. As in Figure 1, here too the response of the 20 keV photons is independent of the value of $\eta_X$, indicating that the albedo at this energy is independent of details of the structure of the ionized skin. However, this is not the case with the photons of $E = 1$ keV, as is clearly evident in the figure. For these photons, the decrease in albedo with decreasing $\eta_X$ leads to a corresponding substantial reduction in the reflected flux at this energy. The response curves peak at a lag $\tau \approx 2h_\times/c$ from the injection of the X-ray pulse, as expected in reflection by an infinite plane for an observer right above the source, indicating that for the chosen value of $\eta_X$, the effects of the absence of the disk for $r \leq 3R_g$ are indeed small.

The effects of changing the observer latitude $\theta$ on the response function are shown in Figure 3. In computing these curves, the values $\eta_X = 0.3$ and $h_\times = 10$ were used, with the usual notation for solid and dashed curves. Decreasing the observer latitude impacts differently the amplitude of the response for the soft (1 keV) and hard (20 keV) X-ray photons: the response of the latter decreases because of the decrease of the disk area projected along the

![Fig. 1.](image1)  
![Fig. 2.](image2)
Viscous dissipation provides for accretion onto a Schwarzschild black hole a total local radiant flux \( F \) of magnitude (see, e.g., Shapiro & Teukolsky 1983)

\[
F = \frac{3GM\dot{M}}{8\pi R^3} \left[ 1 - \left( \frac{R_i}{R} \right)^{1/2} \right], \tag{10}
\]

where \( M \) is the mass of the accreting black hole, \( \dot{M} \) the accretion rate, and \( R_i \) the inner edge of the accretion disk, with \( R_i = 3R_S \) in the case of a Schwarzschild black hole considered here. Let \( \epsilon \) denote the efficiency of the thin disk in converting mass flux to radiation; then the local radiant flux due to the thin-disk thermal emission, \( F_d \), and the corresponding temperature \( T_d \) (assuming blackbody emission) are given by the relation

\[
F_d = \sigma T_d^4 = \frac{3}{16\pi R_S^3} \frac{L_d}{\epsilon} \left[ 1 - \left( \frac{R_i}{R} \right)^{1/2} \right] \chi^3, \tag{11}
\]

where \( R_S = 3 \times 10^{13} M_\odot \) cm is the Schwarzschild radius of the black hole (\( M_S \) is the black hole mass measured in units of \( 10^6 M_\odot \)), and \( \chi \) is the radius normalized to \( R_S \), with \( \chi = 3 \) and \( \epsilon = 0.06 \) in the case of a disk around a Schwarzschild black hole. On the other hand, the reprocessed X-ray flux at radius \( R \) on the disk and the temperature of the associated thermal emission are given by

\[
F_X = \sigma T_X^4 = \frac{L_X(1 - \alpha)}{4\pi(h^2 + R^2)} \frac{h_X}{(h^2 + R^2)^{1/2}}, \tag{12}
\]

where \( L_X \) is the luminosity of the X-ray source, and \( \alpha \) is the energy-integrated, angle-averaged albedo of the disk.

In applying the above considerations to models of the NGC 3516 campaign, because the X-ray luminosity is variable while that of the disk \( L_d \) is assumed to be constant, the value of their ratio \( \eta_X (0.3) \) referred to in the rest of the paper is that observed at the beginning of the monitoring campaign. The instantaneous value of the temperature used in the computation of the variable flux is then given by

\[
T(R, t) = \left[ \frac{F_X(R, t)}{\sigma} + \frac{F_d(R)}{\sigma} \right]^{1/4}. \tag{13}
\]

With the time-dependent temperature as a function of the radius at hand, the flux at a given wavelength \( \lambda \) is obtained by first integrating this emission at a given radius \( R \) over all lags \( \tau \) and then over all disk radii, to get

\[
f_j(t) = \int_0^\infty dR \int_0^{\tau_j} d\tau A(R, \tau) B_j[T(R, t - \tau)], \tag{14}
\]

where \( B_j(T) \) is the blackbody emissivity of temperature \( T \) at wavelength \( \lambda \).

Using the above expression (eq. [14]) and the X-ray light curve of NGC 3516 of Edelson et al. (2000), we produced model light curves at a number of wavelengths in the UV and optical part of the spectrum, specifically at 1360, 3590, and 5510 Å, to allow a direct comparison with those observed. The X-ray light curve used in equation (14) was obtained by a direct logarithmic interpolation of the light curve of Edelson et al. (2000), graciously provided to us by K. Nandra. One should note that the use of equation (14) in computing the model light curves requires the knowledge of the X-ray flux at times prior to that of day 915.8, at which the monitoring campaign began. Given that no information about this flux is available, we assumed it to be constant at

\[
\eta_X = 0.3 \quad \theta = 60, 30, 5 \quad h_X = 10
\]

\[
\eta_X = 0.3 \quad \theta = 60, 30, 5 \quad h_X = 10
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\[
\eta_X = 0.3 \quad \theta = 60, 30, 5 \quad h_X = 10
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\[
\eta_X = 0.3 \quad \theta = 60, 30, 5 \quad h_X = 10
\]
the level it had at the beginning of the campaign. In addition to this problem, one must also allow this constant flux to persist sufficiently long for the reprocessed radiation to reach a steady state level. Not taking this into consideration may result in a model light curve dominated by the X-ray "turn-on" phase. We have experimented with the "turn-on" time and found that for the longest wavelength (5590 Å) and for the largest value of the mass ($M = 10^7 M_\odot$), we should turn the source on at day 912 in order to achieve a steady emission at this wavelength by day 915.8. The effects of a nonconstant X-ray flux prior to the above starting date can be estimated by looking at the results of our runs. They are generally small for $M = 10^7 M_\odot$; however, for $M = 10^8 M_\odot$ and face-on disks, our models exhibit lags of the order of 0.25 day between the X-rays and the reprocessed flux, a fact that indicates the extent to which the prior light curve could impact our models.

In computing the model light curves, we assumed that the X-ray spectrum of NGC 3516 is a power law, i.e., $F_\gamma \propto E^{-\alpha}$ ergs s$^{-1}$ keV$^{-1}$, $\alpha \approx 0.5$ (Nandra et al. 1999) that extends to energies $E \approx 100$ keV, thereby yielding $\eta_\gamma = L_\gamma/L_X = 0.3$. Nandra et al. (1999), who presented the spectral analysis of the X-ray observations of this campaign, concluded on the basis of the Fe Kα line profiles that the disk inclination is small ($\theta$ is large), so that the value of $\eta_\gamma$ (0.3) inferred above is a fair representation of the true value of this parameter because no significant absorption in an obscuring torus is expected for such small inclination angles. We therefore use this value for $\eta_\gamma$ in the remainder of our paper, irrespective of the value of the latitude angle, $\theta$, used.

With the value of $\eta_\gamma$ fixed, we study the effects of the remaining two parameters $\theta$ and $M$ on the model light curves due to X-ray reprocessing. Figure 4 exhibits the relative amplitude of the observed X-ray light curve along with those of the model light curves due to X-ray reprocessing for the three wavelengths considered, namely, 1360, 3590, and 5510 Å for a black hole mass $M = 10^7 M_\odot$, $\eta_\gamma = 0.3$, and $\theta = 30^\circ$. Figure 5 is an expanded version of Figure 4, but exhibiting only the relative amplitudes of the model light curves. Similarly, Figures 6 and 7 exhibit the relative amplitudes of the same light curves for the same values of $\eta_\gamma$ and $\theta$, but a black hole mass of $M = 10^8 M_\odot$.

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**Fig. 4.** X-ray light curve (dotted line) along with the model light curves at 1360 Å (solid line), 3590 Å (long-dashed line), and 5510 Å (short-dashed line) for $M = 10^7 M_\odot$, $\theta = 30^\circ$, and $\eta_\gamma = 0.3$.

**Fig. 5.** Expanded version of Fig. 4, but showing only the model light curves of the reprocessed radiation. The wavelength assignments are the same.

**Fig. 6.** X-ray light curve (dotted line) along with the model light curves at 1360 Å (solid line), 3590 Å (long-dashed line), and 5510 Å (short-dashed line) for $M = 10^8 M_\odot$, $\theta = 30^\circ$, and $\eta_\gamma = 0.3$.

**Fig. 7.** Expanded version of Fig. 6, but showing only the model light curves of the reprocessed radiation. The wavelength assignments are the same.
We also explored the effects of the observer latitude angle \( \theta \) and the height of the source \( h_\beta \) on the resulting light curves. Figure 8 has identical parameters to those of Figure 7 except for the observer latitude, which is \( \theta = 85^\circ \). There is an apparent increase in the lag of the reprocessed light curves relative to those of \( \theta = 30^\circ \), as well as a small increase in the variability amplitude, which for 3590 Å reaches \( \approx 5\% \). Finally, for reasons that will be explained in §5 (the need for higher X-ray flux at small R to improve the spectral fits), we have also produced light curves for the same almost face-on models (\( \theta = 85^\circ \)) but smaller distance of the X-ray source from the disk (\( h_\lambda = 4 \)). The light curve for this set of parameters is shown (along with those of \( h_\lambda = 10 \) for comparison) in Figure 9. The effects of reducing \( h_\lambda \) are a small decrease in the respective lags between all bands and a substantial decrease in the level of variability to the \( \approx 2\% \) level.

The most apparent feature of the model light curves is the smallness of their variability amplitudes, given the large fluctuations (\( \approx 70\% \)) of the X-ray flux. This is the result of the combination of “spreading” the reprocessed emission over a large range of radii and the addition of “diluting” its variations with the (presumably) constant flux intrinsic to the accretion disk. As shown in Figures 5 and 7, the variation amplitudes for 3590 and 5510 Å are of the order of \( \approx 3\%–5\% \); while they are larger and more easily discernible at 1360 Å, the observations in this wavelength are not reliable because of the influence of the South Atlantic Anomaly on the UV detectors. Therefore, one cannot exclude the X-ray reprocessing model on the basis of the observed optical variability amplitudes.

However, despite the agreement in the variability amplitudes between the observed and the model light curves, closer inspection reveals persistent differences in their morphology that put the entire scheme into question: the data (Edelson et al. 2000) exhibit a marked absence of O–UV response to reprocessed emission from the large X-ray flare that peaks at day 916.9 (see Fig. 2 of Edelson et al. 2000). This emission is quite evident in the model light curves and persists for the entire range of parameters explored. Actually, it is the most prominent feature of the model light curves in almost all the cases examined; its preponderance, however, decreases with increasing black hole mass and wavelength. Eventually, for the largest values of the black hole mass and for the longest wavelength (5510 Å), the amplitude of the response to the much broader (and of lower peak flux) X-ray flare between days 917.3 and 920 seems to become the dominant one (see Fig. 7). One might think then that an even larger value for the black hole mass could increase the dominance of this last feature so that the model light curves become similar to those observed (i.e., consists of a single broad peak at day \( \approx 918.5 \)). This may indeed be the case; however, the larger mass increases also the lags between the X-rays and the reprocessed emission to the point that they become inconsistent with those observed.

While lags between the X-rays and the reprocessed optical emission become apparent for \( M_\beta \geq 1 \rightarrow 3 \), our model light curves exhibit no lags between the variations at 3590 and 5510 Å. This is contrary to the rough (and uncertain according to the authors themselves) estimates of Edelson et al. (2000), who argued for the presence of lags \( \approx 0.2 \) day between these two bands. This synchrony can be easily understood by looking at the response function of the lamp-post model in these two wavelengths: these indeed exhibit (for certain values of the parameters) lags, which, however, are much smaller than their widths and the duration of the X-ray flares. Not surprisingly, when convolved with the latter, they yield light curves that vary in unison.

To quantify this specific issue of intraband lags as a function of the black hole mass within our model, we computed the CCFs between the model light curves at 5510 and 3590 Å and also between each of them and the observed X-rays. These are presented in Figures 10 and 11 for \( M = 10^7 \) and \( 10^8 M_\odot \), respectively. These figures indicate no lags in the CCF between the model light curves at 3590 and 5510 Å, in agreement with the arguments given above. However, they do show the presence of lags in the CCF between the X-rays and the model light curves of either wavelength, for both values of the black hole mass. For \( M = 10^7 M_\odot \), the lags are too small (\( \approx 0.1 \) day) to be easily detectable in the light curves of Figure 4. This is not the case for \( M = 10^8 M_\odot \), for which the lag between the X-rays and the optical emission (at either wavelength) is apparent and of the magnitude \( \approx 0.25 \) day, with the lags increasing still further for \( \theta = 85^\circ \).
Unfortunately, the observed CCFs between the same bands are not as sharply peaked as those presented above to allow a direct comparison (see Fig. 6 of Edelson et al. 2000); however, in this latter figure there is some indication that the X-rays precede the optical emission by about 0.25 day.

The interpretation of the above results is not obvious. If we dismiss any correlations between the X-ray and the optical data but fails to reproduce the UV data by a factor of 5. Decreasing the value of the mass to a factor of 5 decreases the discrepancy of the flux in the optical part of the spectrum; however, it increases the UV flux at shorter wavelengths that are not observed. Finally, the combination (\( M_g \approx 0.25, \dot{m} = 0.028 \)) provides a reasonable eyeball fit to the optical data but fails to reproduce the UV data by a large margin. Similar combinations with smaller values of

5. THE DISK SPECTRA

Having obtained a range of values for parameters of the system from the timing observations and constraints, we use these to compute the corresponding O–UV and X-ray reflection spectra, which we then compare to observations. For the O–UV spectra, we make the usual assumption that the local emission is that of a blackbody that irradiates the locally produced luminosity, as done before in the literature. For the X-ray spectra, we use the self-consistent procedure discussed in NKK and further elaborated on in Nayakshin (2000b). This procedure is directly applicable to the generic model whose properties we attempt to test here. This combined spectrotimetral approach puts far more severe and comprehensive restrictions on the specific model than its timing or spectral properties alone. We hope that such a combined approach will eventually point to the direction of a class of models that can accommodate these combined constraints.

5.1. The Optical–UV Model Spectra

The equations used to compute the time-dependent light curves due to X-ray reprocessing on the disk (in particular eq. [14]) can be also used for the computation of the spectra of the geometrically thin, optically thick disk responsible for the O–UV emission. It was argued long ago that the spectra of AGNs in this wavelength range are well fitted by such models (Malkan & Sargent 1982; Malkan 1983; Laor & Netzer 1989; Sun & Malkan 1989). We compute these spectra by assuming the X-ray flux to be constant and compute the resulting flux \( f_\lambda(t) \) for different values of the wavelength rather than the time. The values of the black hole mass, \( M \), and accretion rate (in units of the Eddington rate), \( \dot{m} \), are chosen so that they provide reasonable eyeball fits to the observed O–UV fluxes as given in Edelson et al. (2000). In order to convert our luminosity values (derived from the use of a given value of \( \dot{m} \)) to the observed flux, the value of the Hubble constant \( H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1} \) was used. The results of these calculations are given in Figure 12.

It is apparent from this figure that no single combination of these values provides (even) a rough fit to the combined data. While the values \( M_g \approx 3 \) and \( \dot{m} \approx 0.003 \) (\( \dot{m} \) is the accretion rate in units of the Eddington accretion rate) could presumably provide a reasonable rough fit of the UV data (the flux of this part of the spectrum appears to be constant); they overproduce the optical luminosity by about a factor of 5. Decreasing the value of the mass to \( M_g = 1 \), with a concomitant increase in the accretion rate to \( \dot{m} = 0.009 \) to keep the total luminosity constant, reduces the discrepancy of the flux in the optical part of the spectrum; however, it increases the UV flux at shorter wavelengths that are not observed. Finally, the combination (\( M_g \approx 0.25, \dot{m} = 0.028 \)) provides a reasonable eyeball fit to the optical data but fails to reproduce the UV data by a large margin. Similar combinations with smaller values of
M\(_8\) give spectra that peak at wavelengths too short to provide any useful fits to the UV data.

5.2. The X-Ray Reflection Spectra

We compute the X-ray reflection spectra, assuming that the X-ray spectral index is \(\Gamma = a + 1 = 1.5\), as appropriate for NGC 3516 based on results of Nandra et al. (1999). Further, we use \(\eta_X = 0.3\), exponential cutoff energy \(E_{\text{cut}} = 100\) keV, and two values for the black hole mass, \(10^8\) and \(10^9\) \(M_\odot\). Using the approach described in NKK and the associated numerical code, we compute the reflected spectra at 10 different radii (measured in units of the Schwarzschild radius), \(r_k = r_0 \times 2^{k-10.2}\), where \(r_0 = 3.5\) and \(k = 1, 2, \ldots, 10\), and for 10 different viewing angles. We then define a spectrum for an arbitrary value of \(r\) and any viewing angle to be a linear interpolation of the spectra computed for the nearest values of \(r_k\) and \(r_{k+1}\) as well as viewing angles. Finally, we integrate over the accretion disk surface to obtain the full-disk spectra at a given viewing angle, taking into account the gravitational redshift in the photon energy and Doppler boosting due to Keplerian disk rotation (for a nonrotating black hole). A more complete discussion of this procedure is given in Nayakshin (2000b). In addition, the detailed structure of the illuminated atmosphere of the disk at \(r = 6\) for the lamppost model and the reflected spectra are presented in Nayakshin & Kallman (2001).

Figure 13 shows the reflected spectra at the inclination angle of \(i = 90^\circ - \theta = 13^\circ\) (this angle appears to reproduce the Nandra et al. 1999 Fe line profile best; see below). More precisely, the curves in this figure exhibit the ratio of the observed spectrum (i.e., source + reflected), with the effects of the observer viewing angle in full consideration, to that of the source alone, much in the spirit the ratios of data to model that are presented by the observers. One should note that because the highly ionized skin reflects a large fraction of the photons even at soft X-ray energies, the ratio of the total observed spectrum to the direct-continuum X-ray emission can be substantially higher than unity for all photon energies (see NKK). (Therefore, an observer fitting the spectrum with a power law + reflection from neutral material [which reflects very little at energies \(E \lesssim 5\) keV] would severely underestimate the reflection fraction and therefore the solid angle of the source subtended by the reprocessing ‘cold’ matter [Done & Nayakshin 2001]). Figure 13 demonstrates also the obvious fact that a decrease in the height of the X-ray source leads to a smaller fraction of \(L_X\) intercepted by the disk and therefore to less reflected continuum and Fe K\(_\alpha\) emission (dashed lines).

The spectra corresponding to the black hole mass value of \(M_8 = 0.1\) are rather unusual in the sense that they deviate very strongly from the roughly power-law–type spectra, typical of Seyfert 1 nuclei in the \(\sim 1–15\) keV range. For this value of the mass and the observed X-ray luminosity, the ionized skin of the irradiated disk is Thomson thick but not completely ionized (i.e., “warm”). This leads to an enormous absorption edge (blended with Fe recombination continuum) and a very strong emission feature between \(\sim 1.5\) and 4 keV, which is due to a blend of recombination continua from elements Mg, Si, and S. As discussed in detail in Nayakshin & Kallman (2001), these features, as well as the He-like Fe line at \(\sim 6.7\) keV (further broadened and shifted by Compton scattering and relativistic effects), are due to the presence of this “warm” skin on the disk surface. The absence of these features in the spectrum of NGC 3516, and in the spectra of Seyfert 1 AGNs in general, seems to argue against this smaller value for the black hole mass.

For the larger value of the mass, \(M_8 = 1\), the X-ray flux on the accretion disk is smaller, leading to a correspond-
ingly thinner ionized skin. As a result, even though the skin is still not completely ionized and does include emission from the transitions discussed above, its relative contribution to the reflected spectra is small compared to that of the underlying, neutral, cold layer. Therefore the spectra are much more similar to those observed, which are generally fitted with reflection from “cold,” neutral matter (see, e.g., Basko et al. 1974; Lightman & White 1988; Magdziarz & Zdziarski 1995; Poutanen, Nagendra, & Svensson 1996). The fits of the continuum reflection spectra alone, therefore, seem to favor this larger value for the black hole mass, in sharp contrast to synchrony in the O–UV variations, which is more consistent with the smaller \( (M_s = 0.1) \) value. Let us now make a detailed comparison of the four computed spectra with that observed by Nandra et al. (1999).

### 5.3. The Fe Line Profiles

Much of the significance of the Fe line observations lies in the fact that they are (occasionally) very broad, indicating emission from X-ray reprocessing on cold matter in the black hole vicinity. The Fe line in the spectra of NGC 3516, obtained during the campaign analyzed here, was indeed broad (Nandra et al. 1999), thereby providing additional constraints on the parameters of this system. In the absence of data associated with the Fe line variability, we have attempted to delineate these constraints through the modeling of the line profiles. Note that the line profile is calculated as a part of our full calculation of the X-ray illumination, so that the spectra shown below are the same as those shown of Figure 13, except that we “zoom-in” at the 2–10 keV energy region. In Figure 14 we present the line profiles so computed for two different values of the inclination angle, namely, \( i = 13^\circ \) and \( 26^\circ \) (the two solid lines; the lowest energy line energy corresponds to \( i = 13^\circ \)) and for two different values of the black hole mass \( (M_s = 0.1, 1) \) and X-ray source height \( (h_x = 4, 10) \), along with the best fit to the data by Nandra et al. (1999) (dotted line). The best-fit line profile is rescaled so that its flux matches roughly that of our model disk spectra at \( E \sim 3 \) keV, while its integrated flux matches that of our models.

It is apparent in the figure that none of our line profiles look even approximately similar to that which best fits the data (dotted line). The main reason is the extra flux at \( E \lesssim 5.5 \) keV relative to that of our models. Indeed, in order to provide a fit to the red wing of the line, Nandra et al. (1999) used a very steep law for the X-ray illumination of the disk \( (F_x \propto R^{-4}) \), limiting the emission to a section of the disk located very close to the black hole. We have attempted to simulate this by reducing the X-ray source height \( h_x \). While the resulting line profiles are indeed broader, they still fall far short from matching those of Nandra et al. (1999). This is because of both geometry, which dictates that a larger fraction of \( L_x \) be “wasted” in the hole at \( R < 3R_s \), and also ionization physics: because the illuminating X-ray flux at small \( R \) is now larger than it is for \( h_x = 10R_s \), the skin is more ionized and produces less of the He-like Fe line, leading to an overall decrease in its equivalent width. We do not think that any value of \( h_x \) could produce the required illumination law, at least for a Schwarzschild geometry. Consideration of a Kerr geometry may help in this respect;

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3 A study of the origin of the “absorption” feature reported by these authors is beyond the scope of this paper at this time (but see Ruszkowski & Fabian 2000).

4 Out of curiosity, we computed a full-disk spectrum for \( M_s = 0.1 \) with the Doppler effects turned off and found the line width to be \( \sim 1 \) keV because of Compton scattering in the skin and the presence of He- and H-like ion contributions.
smaller Thomson depth of the skin leads to a narrower line, dominated by the 6.4 keV transitions and broadened by the kinematics of the disk. The Fe absorption edge is neutral-like at $\sim 7.1$ keV, but it is not well seen in the model spectra owing to its blending with the Fe line emission by the combined effects of Doppler and gravitational smearing. There is no noticeable edge/recombination feature at $\sim 9$ keV and also no low-energy (at $\simeq 2$–$4$ keV) Mg, Si, and S features, in agreement with observations (Nandra et al. 1999). The EW of the line is a little low, a fact that could be remedied by allowing for a supersolar Fe abundance (see George & Fabian 1991).

6. SUMMARY AND CONCLUSIONS

We have examined in detail the spectrotemporal properties of the “standard” model of the central regions in AGNs, which consist of a geometrically thin, optically thick accretion disk along with an overlying, illuminating X-ray source at a height $h_\text{s}$, in view of the recent monitoring campaign of NGC 3516 (Edelson et al. 2000). To this end we have produced model light curves due to X-ray reprocessing at the wavelengths observed in this campaign, namely, 1360, 3590, and 5510 Å. Comparison of the timing characteristics (amplitudes, lags between the various wavelengths) of our model light curves to those observed set the range of acceptable values of the parameters that characterize the model, namely, $M$ and $h_\text{s}$. Using values of these parameters derived from the timing considerations, we produced the O–UV continuum, as well as the detailed X-ray reflection spectra expected from the X-ray illumination of the accretion disk, taking into detailed account the ionization, radiative transfer, hydrostatic balance, and kinematic and gravitational effects.

Our results can be summarized as follows:

1. The variability amplitudes of the reprocessed emission at 3590 and 5510 Å are in reasonable agreement with those observed, assuming $h_\text{s} \simeq 10R_\text{g}$. For this value of $h_\text{s}$, the light curves in these two wavelengths vary in synchrony for the entire range of values of the black hole mass examined ($M_\text{g} = 0.1$–$3$), in agreement with observations. Therefore, these two aspects of variability do not impose any serious constraints on the reprocessing models.

2. The detailed morphologies of the observed and the model O–UV light curves are substantially different. Demanding agreement between them (i.e., smearing out the reprocessed emission from the flare at day 916.8) points to values for $M_\text{g}$ in excess of 1. Such values, however, would lead to lags between the X-ray and optical variations difficult to reconcile with those observed. It is in this sense that the data are in disagreement with the reprocessing paradigm.

3. The observed O–UV spectral distribution of NGC 3516 is generally narrower than that of the “standard” accretion disks: a reasonable fit of the UV flux ($M_\text{g} \simeq 3$) overproduces the optical emission, while producing a good fit to the optical flux ($M_\text{g} \simeq 0.1$) places the peak emission at wavelengths far short of the observed 1200–1500 Å, underproducing the observed flux at this range. Interestingly, each mass range is consistent with only one specific aspect of the timing data: the smaller mass with the X-ray–optical variation synchrony and the larger one with the suppression of the X-ray flux feature near day 916.8, in the model light curves.

4. The model X-ray reflection spectra are clearly inconsistent with those observed for the “small” values of the black hole mass ($M_\text{g} \simeq 0.1$), owing to the high Thomson thickness of the not fully ionized skin, which produces atomic transition features not observed in the data. Increasing the mass to $M_\text{g} \simeq 1$ leads to a much smaller Thomson depth of the skin and hence to X-ray reflection spectra resembling those observed (but see next result). Note, however, that high black hole masses lead to disagreement with the timing data (result 2).

5. The Fe line (more accurately the Fe line complex) observations, in conjunction with our models, constrain the inclination angle of the disk to $i \simeq 13^\circ$–$26^\circ$. While our models produce reasonable equivalent widths for this line, they are unable to match, even approximately, the best fit of the observed profile. The main reason is the large red wing of the Fe Kα line extending to $E \sim 4$ keV (Nandra et al. 1999), which requires that most of this emission, and therefore the associated X-ray illumination, be confined to a region very close to the black hole horizon. Reducing the source height $h_\text{s}$ to achieve this does not help since it also reduces significantly the O–UV variability amplitude of the model. An extreme Kerr black hole, which allows the accretion disk to reach to $r < 3R_\text{g}$, could help in this respect; however, quantitative models do not exist for this case; furthermore, it is not apparent how such models would provide a resolution of the issues raised in result 2 above.

Where do all these results leave us? It is apparent that one cannot fulfill all the observational constraints within this picture of the central engine of AGNs. The alternatives are few: (1) ignore some of the constraints as less important or inconclusive and attempt to find concordance within this less restricted constraint list, or (2) abandon this model in favor of an altogether different one. But which one? There does not exist, at present, a paradigm as well defined and generally accepted as the one presented herein.

We tentatively choose to concentrate on the timing constraints as being less equivocal than the spectral ones about the true geometry of the source. Then, motivated by the systematic change toward agreement between model and observed light curves with increasing black hole mass, we favor models with a larger reprocessing region than considered in this note. A way to achieve this is to abandon the pointlike X-ray source assumption in favor of an extended one (a corona?) of size $\sim 0.5$ lt-day. Such extended X-ray sources have been considered in models of the time lags between hard and soft X-ray photons in galactic black hole candidates (Kazanas, Hua, & Titarchuk 1997; Böttcher & Liang 1999; Hua, Kazanas, & Cui 1999; Poutanen & Fabian 1999); their implied sizes are $\sim (50$–$1000)R_\text{g}$, depending on the specific model. Applied to AGNs, these models would yield, if scaled by the black hole mass, a source size roughly equal to that suggested above. The question of whether such a geometry could produce light curves consistent with those observed can be answered only with additional calculations appropriate for such a geometry, to which we hope to return in a future work.

Finally, one cannot exclude an altogether different model that might provide agreement with both spectral and timing constraints. For example, if the X-ray emission originates in magnetic flares of height much smaller than their radial distance from the black hole, the X-ray flux incident on the
disk near a flare would likely be much larger than it is in the lamppost model of the same $L_X$. This could shift the effective temperature of the reprocessed radiation to wavelengths shorter than those used in the campaign of NGC 3516, thus making difficult the interpretation of the timing results. However, quantitative testing of such models requires detailed studies which go beyond the scope of this paper.

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