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ACCRETION DISK EMISSION FROM A BL LACERTAE OBJECT

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ABSTRACT

The accretion disk configuration has features that make it an attractive model for BL Lac objects: a preferred axis defined by jets, implying nonnegligible angular momentum, and high efficiency of radiation production, allowing near-Eddington luminosities. While the smooth continuum spectra of BL Lac objects do not show large UV bumps, in marked contrast to quasars, high-quality simultaneous data do reveal deviations from smoothness. We here suggest that the UV and X-ray emission of BL Lac objects may originate in an accretion disk. Using detailed calculations of accretion disk spectra, we fit the best-measured ultraviolet and soft X-ray spectra of the BL Lac object PKS 2155−304, and determine the mass and accretion rate required. The ultraviolet through soft X-ray continuum is well fitted by the spectrum of an accretion disk, but near-Eddington accretion rates are required to produce the soft X-ray excess. A hot disk or corona could Comptonize soft photons from the cool disk and produce the observed power-law spectrum in the 1–10 keV range. The dynamic time scale in the disk regions that contribute most of the observed ultraviolet and soft X-ray photons are consistent with the respective time scales for intensity variations observed in these two wave bands; the mass derived from fitting the continuum spectrum is consistent with the limit derived from the fastest hard X-ray variability.

Subject headings: black holes — galaxies: nuclei — quasars

I. INTRODUCTION

Accretion disks are an attractive theoretical concept in compact objects like active galactic nuclei (AGNs). Accretion onto a massive black hole is thought to be the ultimate power source of AGNs, and if so, disks or some comparable dissipative mechanism are needed in systems with appreciable angular momentum in order to transfer accreting matter from large radii into the central regions surrounding the black hole. However, the presence of accretion disks in AGNs is far from established. In galactic sources like eclipsing cataclysmic variables, one can see direct evidence for accretion disks (Young, Schneider, and Shectman 1981; Marsh, Horne, and Shipman 1987), but comparable observations in AGNs are impossible because of the long time scales involved. Instead, the strongest evidence for accretion disks in AGNs appears to be the ultraviolet spectral feature known as the "big blue bump," a flattening of the spectrum from the optical into the ultraviolet seen in many quasars and Seyfert galaxies (e.g., Edelson and Malkan 1986). Many have interpreted this spectral excess as thermal emission from a hot accretion disk (Shields 1978; Malkan 1983; Czerny and Elvis 1987; Wandel and Petrosian 1988; Sun and Malkan 1989).

In many broad-line AGNs the big blue bump provides the bulk of the bolometric emission. It stands out clearly as a separate spectral component above an infrared power law, starlight from the host galaxy, and pseudocontinuum from the broad-line region, which together constitute a very "lumpy" broad-band spectrum. In contrast, the spectra of blazars (the collective name for BL Lac objects and optically violently variable [OVV] quasars) are relatively smooth and have no prominent spectral features in the blue or the ultraviolet. For this reason, the possible relevance of accretion disks to blazars has been ignored. Instead, blazar spectra are most often explained with nonthermal processes like synchrotron and synchrotron–self-Compton (SSC) radiation, in general quite successfully (Urry 1988 and references therein). If a significant contribution from an accretion disk were present, one would expect deviations from spectral smoothness—that is, spectral breaks in the infrared-optical-ultraviolet region.

It is not clear that such spectral breaks can be ruled out. First, high-quality broad-band spectra of blazars are harder to obtain than spectra of nonblazars simply because the former are more rapidly variable, so observations must be made within a few hours rather than a few weeks or months. Furthermore, the accretion disk luminosity in blazars may constitute a smaller fraction of their bolometric luminosity than in normal quasars, making spectral breaks more difficult to observe. In fact, it turns out that when one looks carefully at the best available blazar spectra (e.g., Landau *et al.* 1986; Urry *et al.* 1988*b*), one *can* see deviations from smoothness.

In blazars, possibly even more than quasars, there is evidence of substantial angular momentum. The preferred explanation for the rapid variability and high polarization of blazars is that they have relativistic jets pointed more or less in our direction. These would be analogous to the radio jets seen in the plane of the sky in radio galaxies and quasars. Most models for the formation of such jets invoke angular momentum to define the jet axis. In the typical unified picture, even with obscuration (e.g., Barthel 1989), the jet axis defines an open view to the central regions, so it is quite plausible to expect thermal accretion disk emission from blazars.

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Disks of the kind considered in this paper have been considered widely in a number of astrophysical contexts, notably in explaining quasar ultraviolet spectra. In that context, we think it useful to model the spectrum of a BL Lac object with a similar model, whether or not it turns out eventually to be an adequate representation of the physical conditions in the centers of AGNs.

In this paper we describe the first application of accretion disk theory to the interpretation of blazar spectra, specifically the spectrum of the luminous, rapidly variable, X-ray–bright BL Lacertae object PKS 2155−304. This object is unique in many ways. The most important for our purposes is that it was the only BL Lac (indeed the only extragalactic object) detected with the high-resolution soft X-ray objective grating spectrometer (OGS) on the *Einstein Observatory* satellite (Canizares and Kruper 1984). No other soft X-ray spectrum of comparable resolution exists. Furthermore, there is a nearly simultaneous ultraviolet spectrum of PKS 2155−304, obtained with the *International Ultraviolet Explorer* (*IUE*). Together these data, because of their simultaneity and their close approach in frequency space, define the ultraviolet–soft X-ray spectral emission of this BL Lac object better than any other data for any other extragalactic object.

We will show that a simple model for emission from a thin, cool accretion disk provides a very good fit to the ultraviolet–X-ray spectrum of PKS 2155−304. The basic model and possible modifications are discussed in § II. The spectral data for PKS 2155−304 and the model fitting are described in § III. In § IV we explore one of the predictions of the model, namely, the variability time scale as a function of wavelength, and we compare it with the available observations. The two independent estimates of the black hole mass, one from spectral fitting and one from variability time scales, are in good agreement. Our results are summarized in § V.

II. MODEL

a) *Disk Structure*

In order to fit the X-ray (soft and hard) spectrum, our model uses two solutions of the accretion disk simultaneously. (1) The steep, soft X-ray spectrum is fitted by the Wien part of the thermal emission from the inner region of the standard thin accretion disk (Shakura and Sunyaev 1973), which also produces the fit to the UV spectrum. In its inner region, close to the black hole, this disk becomes quite hot ($\sim 10^7$ ergs s^{-1}) and capable of emitting soft X-rays. This nevertheless requires near-Eddington accretion rates, and the cool disk has to extend down to the inner boundary. (2) The hard X-ray power-law is produced by a hot, two-temperature (i.e., $T_e \neq T_i$) accretion disk, where the electron temperature reaches $\sim 10^9$ K. A similar model was suggested by Shapiro, Lightman, and Eardley (1976, hereafter SLE) to explain the spectrum of Galactic X-ray sources. In the present work, however, we investigate mainly the "sandwich" or the stratified mode, where the hot and cool components are separated not radially, as in SLE, but vertically, the hot disk forming an optically thin torus above and below the cool, geometrically thin disk. (We find that for a massive black hole it is difficult to produce the steep soft X-ray feature in the radial configuration, because the inner thin disk does not reach high enough temperatures.) In the stratified configuration, the UV and soft X-ray photons from the cool disk have to radiate through the hot disk, some fraction of them being Compton-upscattered to form the hard X-rays.

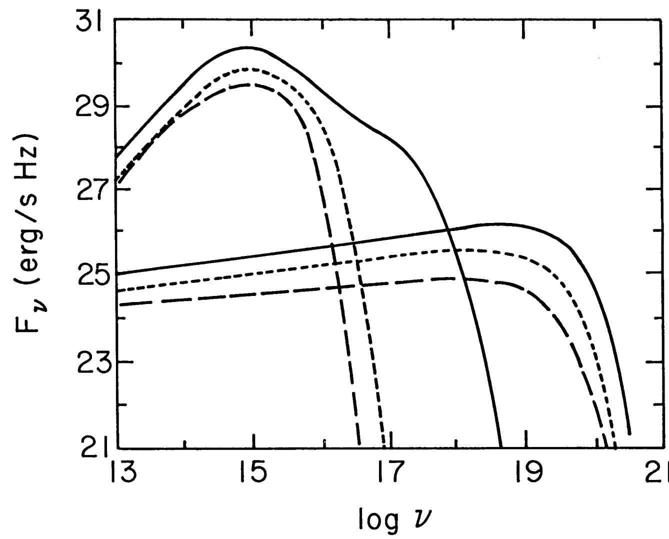

FIG. 1.—Accretion disk spectra for the cool (modified blackbody) and hot (Comptonized bremsstrahlung) accretion disk models, for $L/L_{\rm Edd}$ = 1, 0.1, and 0.01.

The cool disk has been discussed in detail elsewhere (our specific model is described in Wandel and Petrosian 1988). In this section we focus on a hot disk, similar to the one described by SLE and Wandel and Liang (1990).

While in the cool disk Comptonization is only marginally important, it plays an important role in the hot disk. The solution for the Comptonized bremsstrahlung disk and its spectrum give flat bremsstrahlung-like spectra, shown in Figure 1 (see Wandel and Liang 1990). However, if a source of soft photons is present, e.g., a cool disk, inverse-Compton cooling dominates bremsstrahlung cooling, and the disk structure and spectrum are determined by the ratio between the energy in the soft photon input and the hot component, as described below.

We consider a combination of a cool and a hot disk in two configurations: (1) a cold outer disk joined to a hot inner disk (as in SLE), and (2) a cold, geometrically thin disk with a hot, geometrically thicker disk above and below it. In both cases the hot disk will scatter some of the soft photons from the cold disk. In case 1 the scattered fraction is given by the geometrical covering factor of the hot disk as seen from the outer radii of the cold disk, and in case 2 it is given by the optical depth to electron scattering (assuming it is optically thin).

We assume that the main cooling mechanism is inverse-Compton scattering of the soft photons from the cool disk. The inverse-Compton cooling rate is given by (e.g., Rybicky and Lightman 1979)

$$F_{\rm C} = hU_s cn\sigma_{\rm T}(4\theta + 16\theta^2) \quad {\rm ergs\ s^{-1}\ cm^{-2}}\,, \qquad (1)$$

where h is the scale height, $\tau_{\rm es} = nh\sigma_{\rm T}$ is the optical depth to electron scattering, $\theta = kT/m_e c^2$, and U_s is the soft photon energy density. [This formula is accurate only in the optically thin limit ($\tau_{\rm es} \ll 1$), but we use it as an approximation in the $\tau_{\rm es} \leq 1$ regime.] It is convenient to express U_s in terms of the total energy flux from the disk, $Q = 3GM\dot{M}\phi/8\pi R^3$ (ϕ is a correction at the inner disk boundary), and the Compton energy enhancement factor $\eta = Q/cU_s$. Equation (1) can then be written in the form

$$F_{\rm C} = 4\eta^{-1}Q\tau_{\rm es}\,\theta(1 + 4\theta)\,. \qquad (2)$$

In the presence of a copious soft photon source, inverse-Compton cooling dominates, so equating Q with F_C gives

$$\tau_{es} = [4\eta^{-1}\theta(1 + 4\theta)]^{-1} , \quad (3)$$

The solution of the unsaturated-Compton hot disk is (Wandel and Liang 1990; see also Liang and Thompson 1979)

$$T_e = 3.5 \times 10^8 \eta^{1/2}(1 + 4\theta)^{-1/2}\Theta_*^{1/3}\alpha^{-1/6}L_*^{-1/6}r^{1/4} , \quad (4a)$$

$$\tau_{es} = 3.6\eta^{1/2}(1 + 4\theta)^{-1/2}\Theta_*^{-1/3}\alpha^{1/6}L_*^{1/6}r^{-1/4} , \quad (4b)$$

and

$$h = (2 \times 10^{12}\ \mathrm{cm})\eta^{-1/4}\Theta_*^{1/6}\alpha^{-7/12}M_8 L_*^{5/12}r^{7/8} , \quad (4c)$$

where $r = Rc^2/GM$, $L_* = \phi L/L_{\mathrm{Edd}}$, and

$$\Theta_* = \left(\frac{T_i - T_e}{T_i + T_e}\right)(1 + \theta^{1/2})\left(1 - \frac{P_{\mathrm{rad}}}{P}\right) . \quad (5)$$

From equation (4a) it is seen that the temperature is weakly dependent on the parameters, and is high enough to produce the hard X-ray spectrum. For most of the parameter space the scale height (eq. [4c]) is sufficiently small ($h \ll R$) that the thin disk approximation holds.

b) *The Spectrum*

The cool and hot disk solutions produce very different spectra. In the standard cool disk the inner region may become optically thin (for near-Eddington accretion rates), reaching temperatures of 10^7 K and producing a steep soft X-ray spectrum, but it is not hot enough to yield hard X-rays. The hot disk, on the other hand, reaches electron temperatures of a few times 10^9 K, so it can produce hard X-rays, but the spectrum is a featureless power law.

For the standard geometrically thin accretion disk model we use a self-consistent iterative scheme to calculate the local surface temperature of the disk, then calculate the local spectrum with modifications due to effects of electron scattering and Comptonization as described by Wandel and Petrosian (1988), and integrate over the entire disk to find the spectrum. It is found that the contribution to the UV band comes mostly from the inner, electron-scattering–dominated region of the cool disk, where the locally emitted radiation has a modified blackbody spectrum. The spectrum emitted by the hot disk is essentially bremsstrahlung, unless a soft photon source is present, in which case the spectrum becomes a power law. Since Comptonized bremsstrahlung spectra do not actually resemble the observed hard X-ray power-law spectrum of AGNs, we will concentrate on the unsaturated Compton hot disk.

In the case of a hot disk with a soft photon source, if the Comptonization is not saturated, the soft photons will be upscattered into a power-law distribution, with a spectral index given by (Zdziarski 1985)

$$\alpha_{hx} = -\frac{\ln P_\tau}{\ln(1 + 4\theta + 16\theta^2)} . \quad (6)$$

where

$$P_\tau = 1 - \frac{3}{8\tau_{es}^3}[(2\tau_{es}^2 - 1) + e^{-2\tau_{es}}(2\tau_{es} + 1)] \approx \begin{cases} \frac{3}{4}\tau_{es} , & \tau \ll 1 , \\ 1 - \frac{3}{4}\tau_{es} , & \tau \gg 1 . \end{cases}$$

This formula is good for mildly relativistic temperatures, $\theta \gtrsim 0.2$, and τ_{es} less than a few. Substituting θ from equation (3) and τ_{es} from equation (4b) gives

$$\alpha_{hx} = -\frac{\ln P_\tau}{\ln(1 + \eta/\tau_{es})} \approx \frac{\ln C_L - \frac{1}{2}\ln\eta + \ln\frac{3}{4}}{\ln(1 + \eta^{1/2}C_L)} , \quad (7)$$

where

$$C_L = \eta^{1/2}/\tau_{es} = 0.28\Theta_*^{1/3}(1 + 4\theta)^{1/2}\alpha^{-1/6}L_*^{-1/6}r^{1/4} .$$

That is, the high-energy spectral index depends primarily on η, the Compton energy enhancement factor.

In the next section we fit the continuum spectrum of the BL Lac object PKS 2155−304 with the cool disk model, and we discuss the possible influence of an additional limited hot disk component.

III. FITTING THE ULTRAVIOLET–X-RAY SPECTRUM OF PKS 2155−304

a) *Observations*

The bulk of the cool accretion disk luminosity is produced in the ultraviolet–soft X-ray bands. Most X-ray experiments (e.g., the currently operating *Ginga* or *MIR Kvant* detectors) have energy thresholds too high to be sensitive to this emission, for which the maximum energy is a few hundred electron volts. The softest X-ray experiments that have flown in the past include the *Einstein Observatory* imaging proportional counter (IPC), which detected photons with $E > 0.2$ keV, and the *EXOSAT* low-energy (LE) experiment, which reached still lower energies, but neither experiment had the spectral resolution to characterize soft excesses in individual objects. (The combined *EXOSAT* LE/ME or *Einstein Observatory* IPC/MPC could detect soft excesses unequivocally in individual objects but were insensitive to their detailed shape [Turner and Pounds 1989; Urry *et al.* 1990; Wilkes *et al.* 1990.]) The *Einstein Observatory* solid state spectrometer had better energy resolution but had an energy threshold of ∼500 eV, too high for our purposes.

The only soft X-ray experiment with reasonably good energy resolution was the *Einstein Observatory* objective-grating spectrometer (OGS), and the only extragalactic object detected with the OGS was the BL Lac object PKS 2155−304 (Canizares and Kruper 1984), which is one of the brightest BL Lac objects in the soft X-ray band. The OGS spectrum shows a remarkable absorption feature between 600 and 700 eV, which may be due to a hot outflowing wind in the source or to an intervening, hot, intergalactic medium (Canizares and Kruper 1984; Krolik *et al.* 1985). Even more interesting for our purposes is the very steep spectrum from 300 to 600 eV, with $\alpha_{sx} \sim 5$. In contrast, the simultaneous ultraviolet spectrum is relatively flat, with $\alpha_{uv} = 0.95 \pm 0.06$ (Urry *et al.* 1988*a*).

The extrapolation of the ultraviolet spectrum intersects the soft X-ray flux exactly at 10^{17} Hz, as can be seen in Figure 2. Unless the continuum is discontinuous in the extreme ultraviolet, a change in slope $\Delta\alpha \sim 4$ must occur extremely abruptly. A break this sharp is difficult to explain with standard synchrotron models (e.g., Tucker 1967, but see Schlickeiser 1984) but can be fitted very well by our accretion disk model, as discussed in § III*b*.

Above 600 eV the OGS spectrum flattens significantly to $\alpha_{hx} \sim 1.9$, and this emission extends to 10 keV with more or less the same power-law index, as seen by a number of different experiments over the years (Urry and Mushotzky 1982; Urry, Mushotzky, and Holt 1986; Treves *et al.* 1989). This is still quite steep, but it cannot be well fitted by the standard cool

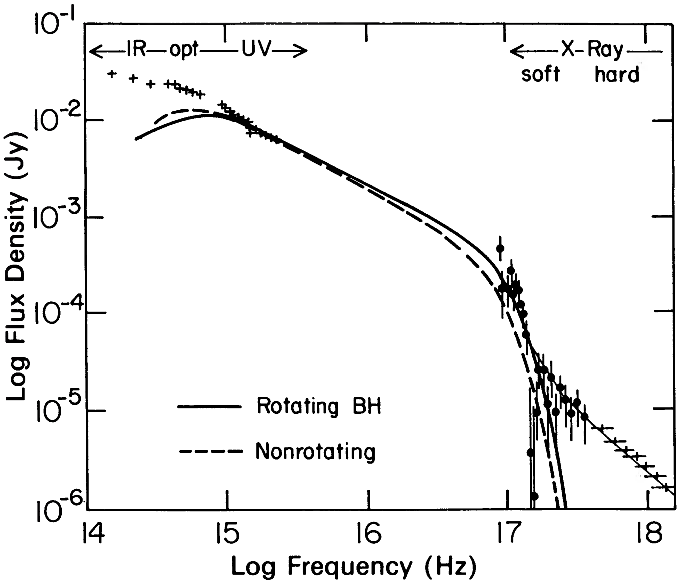

FIG. 2.—Best fit to the spectrum of PKS 2155−304 using a cool accretion disk model for both Schwarzschild (*dashed curve*) and maximally rotating Kerr (*solid curve*) black holes. The accretion parameters for the Schwarzschild (Kerr) model are $L/L_{\rm Edd} = 1.1$ (0.6), $M = 2.3$ (7) $\times 10^8 M_\odot$, and $\alpha = 0.2$ (0.15). The hard X-ray power-law spectrum is produced by a hot disk with the same parameters (see text). The hard X-ray, infrared, and optical data are taken from Treves *et al.* (1989); the simultaneous soft X-ray and ultraviolet data are from the *Einstein Observatory* OGS (Canizares and Kruper 1984) and from *IUE* (Urry *et al.* 1988*a*), respectively.

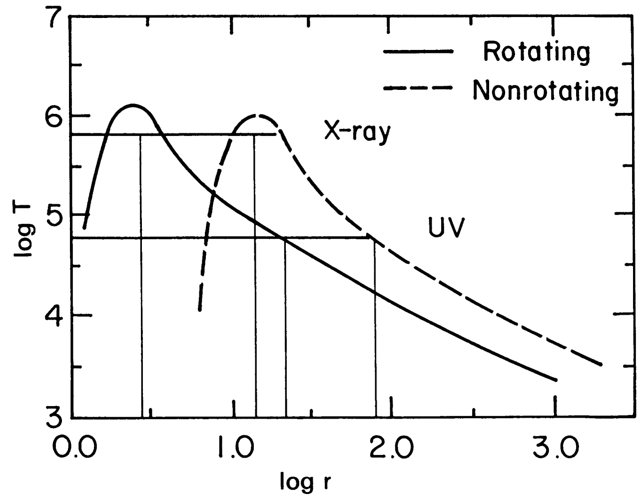

FIG. 3.—Temperature profiles for the Kerr (*solid curve*) and Schwarzschild (*dashed curve*) models shown in Fig. 2. The horizontal lines mark the soft X-ray and UV temperatures. The intersection of these lines with the temperature profiles gives the characteristic radii (in terms of the gravitational radius) emitting in the respective spectral bands.

accretion disk model. In § III*c* we consider the possibility that this hard X-ray spectrum is associated with a hot, two-temperature accretion disk.

b) Fitting the Spectrum with a Cool Disk

We approximate the ultraviolet–soft X-ray spectrum of PKS 2155−304 in Figure 2 by two power laws, one from 1200 to 3000 Å and one from 300 to 600 eV. (This suffices because of the limited spectral range of the data in each wave band relative to the total wavelength range covered.) We then determine the parameters of the cool accretion disk model that give the best fit to the ultraviolet and X-ray power-law slopes and luminosities. (We use $H_0 = 100$ km s^{-1} Mpc^{-1} and $q_0 = 0$ throughout the paper.)

Specifically, fitting the observed spectrum constrains the central mass, mass accretion rate, and viscosity parameter to a narrow region of parameter space. The allowed region is broadened by freedom in choosing the inclination angle, the spin of the black hole (rotating or not rotating), the observational uncertainties, and uncertainties in the model approximations. We assume that the disk is face-on, and we investigate both nonrotating (Schwarzschild) and maximally rotating (Kerr) black holes.

The best fits to the spectrum of PKS 2155−304 are shown in Figure 2. The Schwarzschild solution (*dashed line*) requires a near-Eddington luminosity, the Kerr solution (*solid line*) somewhat less. The parameters of the best-fit models are given in Table 1; the best-fit masses are a few times $10^8 M_\odot$, and the viscosity is $\alpha \sim 0.2$. The temperature profiles of the best-fit rotating and nonrotating black hole disks are shown in Figure 3. Note that the accretion disk model explains only the ultraviolet and soft X-ray bands; data in other spectral bands (infrared, radio) cannot be explained by the standard cool disk model and must come from other processes.

One difference between the spectral fitting of normal quasars and of BL Lac objects is that the former appear to have a sharp break between the infrared power law and the big blue bump, suggesting that these wave bands are produced by separate components, while BL Lac objects have a much smoother infrared through ultraviolet continuum. In order to avoid a break between the infrared and the ultraviolet components, the slope of the infrared power law must be comparable to the ultraviolet disk component, which in this band has a power-law index of 0.4–1 produced by the electron-scattering–dominated region of the disk. The rough continuity of infrared-optical spectrum and ultraviolet spectrum is a potential problem for this model. The spectral shape of an infrared-optical power law must be within a fairly narrow parameter range in order to join smoothly with the disk model. Still, it is clear that BL Lac spectra, while smoother than quasar spectra, are not completely smooth (e.g., Landau *et al.* 1986). Frequently the ultraviolet is flatter than the optical (which is confused in some cases by substantial galaxy light.) Furthermore, the optical and infrared data are not simultaneous. Therefore, we do not think the apparent spectral smoothness is, at present, a serious objection.

The $L/L_{\rm Edd}$ ratio derived from the accretion disk model for PKS 2155−304 is larger than for "normal" quasars (e.g., Padovani 1989; Wandel 1990). This agrees with previous studies in which the Eddington ratios of a number of quasars and BL Lac objects were estimated from the variability time scales (Bassani, Dean, and Sembay 1983; Barr and Mushotzky

TABLE 1

PARAMETERS OF BEST-FITTING MODELS

Black Hole Type	$L/L_{\rm Edd}$	$M/M_\odot$	α
Kerr	0.6	7×10^8	0.15
Schwarzschild	1.1	2.3×10^8	0.2

1986). The short variability times for BL Lac objects imply small masses, which combined with high luminosities lead to $L/L_{\rm Edd}$ ratios close to unity.

c) *Constraints on a Hot Accretion Disk*

While a cool disk model can produce a good fit to the ultraviolet and soft X-ray spectra, it falls short of explaining the hard X-ray component, a power law of index $\alpha_{\rm hx} \sim 1.5$–2 from 0.6 to 10 keV. One could argue that the hard X-rays are unrelated to the disk, but it is worth considering whether they could be associated with a hot disk component.

The spectral index of bremsstrahlung emission from the hot disk has a flat or slightly rising spectrum, much flatter than the observed hard X-ray spectrum. We therefore consider combinations of the cool disk and the hot disk, where Comptonization produces a power law. One possibility is an outer cool disk plus an inner, hot, two-temperature torus, as in the model of SLE, who chose the transition radius, $r_{\rm rad}$, at the point where radiation pressure becomes dominant and the α-disk model becomes unstable. In their model, the outer cool disk produces a UV bump, some fraction of which is Comptonized by the hot disk into a high-energy power law. In our case such a model cannot fit the observed steep soft X-ray excess because the temperature at $r_{\rm rad}$ is too low (Wandel and Petrosian 1988):

$$T(r_{\rm rad}) = (1.5 \times 10^4 \text{ K})(\alpha M_8 L_*)^{-2/7} . \qquad (8)$$

A higher temperature is reached if the transition to the hot disk is chosen at the radius $r_{\rm th} \approx 150 L_*^{2/3}$ at which the cold disk becomes optically thin. The temperature of the cool disk at this radius is (Wandel and Petrosian 1988)

$$T(r_{\rm th}) = (2.8 \times 10^5 \text{ K})\alpha^{-3/8}(M_8 L_*)^{-1/4} . \qquad (9)$$

For the parameters of the best spectral fit this gives $\sim 3 \times 10^5$ K, still too low to explain the soft X-ray emission of PKS 2155−304, though only by a modest factor of 2–3. Since in the optically thin regime the temperature of the cold disk rises inward steeply, a high enough temperature will be reached not far from $r_{\rm th}$. While the temperature condition is satisfied, there is another condition, namely, the relative energy in the ultraviolet–soft X-ray and hard X-ray components.

A different configuration is that the two solutions coexist spatially, with the hot disk like a corona above the cold disk. In this case one must take into account the interaction between the two components, including Compton upscattering of soft photons from the cold disk by the coronal hot disk and reprocessing of the radiation from the hot disk by the cool disk. The latter may be neglected, if the energy output from the cool disk is larger than the luminosity of the hot corona by a factor of 10, as in the present case.

We now try to fit the hard X-ray spectrum with the hot disk model described in § II*a*, without readjusting the parameters of the cold disk. The observed spectrum allows us to make some simple statements about the properties of the hot disk. The hot phase must be sufficiently optically thin to electron scattering so that the soft photons from the cool disk are not over-Comptonized, since this would produce a flatter soft X-ray slope than is observed. From Figure 2 we see that the steep spectrum drops by a factor of ~ 10 in flux density before it becomes comparable to the hard X-ray flux, indicating that only a small fraction of the photons from the cool disk are Comptonized.

For PKS 2155−304 (Fig. 2), the luminosity in the hard X-ray component is $\sim 10\%$ of the luminosity in the ultraviolet–soft X-ray component. Since the amplification by the thin hot phase is of order unity, this is also approximately the ratio of accretion rates of the hot and cold components, in the notation of § II,

$$\eta = Q_h/Q_c \sim \dot{M}_h/\dot{M}_c \sim 0.1 . \qquad (10)$$

The surface density of the hot disk is much lower than that of a cold disk with similar parameters; e.g., for a cold α-disk we have (Shakura and Sunyaev 1973)

$$\tau_{\rm es} = 0.06\alpha^{-1}L_*^{-1}r^{3/2} . \qquad (11)$$

For $\alpha = 0.2$, $r = 10$, $L = 0.5L_{\rm Edd}$ this gives $\tau_{\rm es} = 50$. Comparing this with $\tau_{\rm es} = 0.1$ required in the hot inverse-Compton solution, we find the ratio of surface densities in the cold and hot phases $\Sigma_c/\Sigma_h = 500$, and it increases at larger radii (cf. eq. [4b]). Since the radial inward drift velocity is given by $v_r = \dot{M}/\Sigma$, and $\dot{M}_h/\dot{M}_c = \eta$, this result implies that the radial inflow velocity in the hot phase is 50 times larger than in the cold phase. It is not clear, however, how this difference influences the variability time scale in the hot phase, since the soft photon supply has the time scale of the cold disk, which dominates the energy supply. One could speculate that if variability depends on the radial inflow time scale (e.g., if it is caused by changes in the mass accretion rate), the time scale for changes in the soft X-rays should be approximately equal to or longer than that for the hard X-rays.

A Monte Carlo calculation of the spectrum in this geometry shows that it is possible to reproduce all the observed characteristics for an appropriate choice of the parameters (Fig. 4): a factor of ~ 10 drop in the soft X-ray spectrum of the transmitted spectrum and a steep ($\alpha_{\rm hx} \sim 2$) hard X-ray spectrum require $\tau_{\rm es} = 0.1$ and $kT_e \sim 1 \times 10^9$ K). The energy ratio for that case is $\eta = 1.14$.

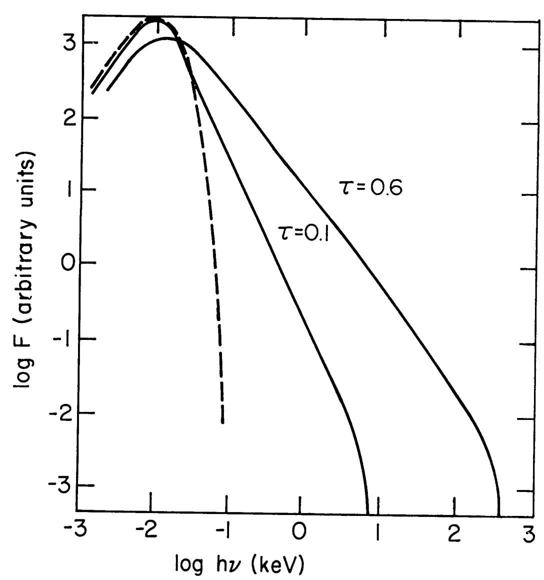

FIG. 4.—Spectrum of the cool disk embedded in a hot, optically thin disk of larger scale height. The spectrum is calculated by a Monte Carlo technique. The properties of the Comptonizing hot disk are consistent with those required to fit the hard X-ray spectrum of PKS 2155−304. The dashed curve is the soft photon input, and the solid curves are the Comptonized spectrum; a coronal disk of $\tau = 0.1$ and $T = 8 \times 10^8$ K produces a hard X-ray slope of 2.2 and a Compton amplification factor of $\eta = 1.15$, while the spectrum marked $\tau = 0.6$ ($T = 5 \times 10^8$ K) has a slope of 1.4 and $\eta = 3.5$.

This agrees with the constraints derived from the approximate analytical equations: an optical depth of $\tau_{es} \sim 0.1$ in the hot disk satisfies the optically thin condition and produces hard X-ray emission with slope (eq. [6]) $\alpha_{hx} \sim 2$ for $T_e \sim (1\text{–}2) \times 10^9$ K. At the same time, equation (7) shows that a slope of 2 for $L/L_{Edd} = 0.3$ and $r = 10$ requires $\eta = 1.12$, in rough agreement with the observed ratio of cold to hot disk emission in PKS 2155−304.

IV. VARIABILITY AND THE CENTRAL MASS

The parameters of a particular accretion disk model determine its temperature profile and therefore the radius associated with emission of a given frequency. For a disk with a moderate temperature profile (see below), one can show that this radius is approximately given by

$$h\nu_* \sim kT(R) . \quad (12)$$

At larger radii the temperature is lower, and since the modified blackbody spectrum peaks at $x = h\nu/kT = 1.2$, the emission at ν_* is negligible because it falls beyond the Wien cutoff. At smaller radii ν_* lies in the Rayleigh-Jeans part of the spectrum ($f_\nu \propto \nu^2 T$), and the surface-area–weighted flux scales as $R^2 T$. If the disk temperature (surface temperature in the optically thick regime) rises inward less steeply than $T \propto R^{-2}$, the emission at a frequency ν_* peaks at the radius where $T(R) = h\nu_*/k$. From Figure 2 we see that $T_s \propto R^{-1}$ in the ultraviolet. In the soft X-ray regime the temperature rises more steeply, but there the disk reaches its highest temperature in a fairly small range of radius (this is implicity required by the fitting of a cutoff at the soft X-ray band) and condition (14) is satisfied.

The time scale for variations in a given spectral band can be related to three characteristic time scales of the emitting region at that radius: the light-travel time, R/c; the dynamical, or Keplerian time,

$$t_d \sim R/v \sim (R^3/GM)^{1/2} \sim 500 M_8 r^{3/2} \text{ s} , \quad (13)$$

where $r = Rc^2/GM$ is the radius in terms of gravitational radii; and the viscous or radial drift time,

$$t_{vis} \sim h\rho/\dot{M} \sim \alpha^{-1}(R/v)(h/R)^{-2} \text{ s} . \quad (14)$$

Of these, the first would reflect changes due to radiative flux emerging radially; the second is the fastest time scale for the growth of instabilities; and the third is the time scale for changes due to local variations of the accretion rate, as would occur if the accreted material were clumpy. The black hole mass can then be related to the variability time. For example, assuming that the observed variations are due to instabilities on the dynamical time scale yields

$$M \approx c^3 G^{-1} r^{-3/2} \Delta t \approx (2 \times 10^7 \, M_\odot)(r/10)^{-3/2} \Delta t(\text{hr}) . \quad (15)$$

Besides having the best simultaneous ultraviolet–soft X-ray spectrum of any BL Lac object, PKS 2155−304 also has the highest quality ultraviolet light curves (Urry *et al.* 1988*a*). Even so, the available data, all obtained with the *IUE* satellite, are quite inadequate for variability studies. Short time scales ($\Delta t <$ hours) are not sampled because the integration times are long, and intermediate time scales are poorly sampled because the sampling is sparse in general. Having said this, we know that variations by a factor of 2 have occurred over 1 yr, and smaller changes (10%–30%) have been seen over intervals of days to weeks. Our best estimate of the characteristic variability time scale is 10^3–10^4 hr (from data in Urry *et al.* 1988*a*).

The X-ray variability time scale is much better known, in part because it is relatively short and in part because the light curves are sampled much better. Several large X-ray flares have been seen from PKS 2155−304 (Snyder *et al.* 1980; Urry and Mushotzky 1982; Morini *et al.* 1986; Urry, Mushotzky, and Holt 1986), but at the softest X-ray energies ($E \leq 600$ eV) the best measurement is the factor of 2 change in flux during the 50,000 s OGS integration (Canizares and Kruper 1984).

We can compare the observed variability time scales with those predicted from the accretion disk models that best fit the spectrum of PKS 2155−304. Table 2 shows the characteristic radii and various time scales (light-crossing, dynamical or Keplerian, and viscous) appropriate to the ultraviolet- and X-ray–emitting regions for each of the two model fits from § III, together with the observed variability time scales. In both wave bands the observed time scales are comparable to or less than the viscous time scales but larger than the dynamic time scales. In other words, *we are able to fit the ultraviolet and X-ray spectra and their respective variability time scales with a single accretion disk model.*

Variations in intensity can give a strict upper limit on the size of the emitting region (in the absence of relativistic effects), $R < c\,\Delta t$, where Δt is the characteristic time for variability. This can lead to an interesting limit on the black hole mass (and on the Eddington ratio) when the emitting region is close to the black hole:

$$M < (1 \times 10^8 \, M_\odot)(r/3)^{-1} \Delta t(\text{hr}) \quad (16)$$

(Wandel and Mushotzky 1986). Using the shortest flux-doubling time scale observed in hard X-rays for PKS 2155−304 (1 hr; Morini *et al.* 1986) and $r = 3$, equation (16) gives $M < 3 \times 10^8 \, M_\odot$, consistent with the accretion disk–modeled mass.

V. CONCLUSIONS

We have showed that the spectrum of a standard, optically thick, geometrically thin accretion disk gives a good fit to the best-measured ultraviolet through soft X-ray spectrum of a

TABLE 2

PREDICTED AND OBSERVED VARIABILITY TIME SCALES

Wave Band	Black Hole Type	r	R (cm)	t_{lc} (hr)	t_d (hr)	t_{vis} (hr)	t_{obs} (hr)
Soft X-ray	Kerr	4	4×10^{14}	4	8	50	14
	Schwarzschild	15	5×10^{14}	5	18	100	
Hard X-ray	...	...	...	...	...	...	1
UV	Kerr	20	2×10^{15}	19	86	6×10^4	$\leq 10^3$–10^4
	Schwarzschild	80	3×10^{15}	25	230	1×10^5	

particular BL Lac object, PKS 2155−304. The model simultaneously fits the spectral slopes and luminosities in the ultraviolet and soft X-ray regimes, and predicts variability time scales that are consistent with observations. Thus it seems that accretion disk emission could be an important source of luminosity in BL Lac objects. If this model is correct, the bulk of the bolometric luminosity is in the far-ultraviolet and is produced in the inner regions of a cool accretion disk.

The hard X-ray emission ($E > 0.6$ keV) from PKS 2155−304 cannot be explained by the cool accretion disk and may be due to an entirely independent component. However, we have considered the possibility of a low-mass, hot, two-temperature disk surrounding the cold disk and Comptonizing the soft photons. The observed hard X-ray emission is roughly 10% of the luminosity of the integrated ultraviolet through soft X-ray emission, which limits the mass accretion rate in the hot disk, and its optical depth must be low because there is no spectral distortion of the steep soft X-ray spectrum. For $\dot{M}_{\rm hot}/\dot{M}_{\rm cool} \sim 0.1$ and $\tau_{\rm es} \sim 0.1$, a rough calculation shows that Comptonization in the hot disk can produce the observed hard X-ray slope ($\alpha_{\rm hx} \sim 2$) and luminosity. This was verified with Monte Carlo calculations of the Comptonized spectrum, but such solutions, where the cool and hot disks coexist spatially, should be investigated more rigorously, taking into account the interactions we have neglected.

We can compare the number of model parameters with the number of observables fitted by this procedure by noting that the structure of the cool disk (M, $\dot{M}$, and α) is determined by fitting the UV and soft X-ray data (which can be roughly represented by four parameters: the luminosity and spectral slope in each of the two bands). The hard X-rays add two additional constraints (hard X-ray flux and spectral index). In the model with a cool disk plus inner hot disk, M and $\dot{M}$ (which must be the same) and α (which could, in principle, be different from α in the cool disk) determine the structure of the hot disk. The only new free parameter is the transition radius; the luminosity produced by the hot disk depends on M, $\dot{M}$, and α, and the disk scale height (hence the fraction of intercepted soft photons from the cool disk) are determined self-consistently from the disk equations. In the case of the cool disk completely surrounded by hot disk, there is also only one new free parameter, the accretion rate.

The spectrum of PKS 2155−304 is unique in that data of similar quality for other BL Lac objects are not presently available. Still, the accretion disk model can be further tested in several ways. First, the ultraviolet variability time scale in PKS 2155−304 can be measured. This requires a well-sampled ultraviolet light curve, which for variability time scales of days might be marginally accessible with *IUE* given enough observing time (100–1000 integrations lasting less than 1 hr evenly spaced over a month or more). Shorter time scales or other fainter BL Lac objects can only be measured with the *Hubble Space Telescope*, with the possible exception of a few high-redshift BL Lac objects that could be measured from the ground. Second, one should look for correlated variations in the hard X-ray and ultraviolet bands to see whether the hard X-rays could be Compton-scattered photons from the cool disk. The hard X-rays should lag the ultraviolet photons, and if the variability is caused by changes in the accretion rate, the time scale should be comparable to or larger than the hard X-ray variability. Correlation studies may be possible with current multiwavelength observations using *IUE* and *Ginga*, provided that the temporal coverage is sufficient. Other tests, like fitting the spectra of other BL Lac objects or measuring the soft X-ray variability time scales, require X-ray spectrometers of sufficient resolution and sensitivity. Some observations of this kind may be possible with *ROSAT*; others may require the higher spectral resolution of *BBXRT*, *Astro-D*, or even *AXAF*.

A further test of this model is the polarization of the UV spectrum. AGNs show a low polarization in the visual band, less than the prediction of a naive accretion disk model. Laor, Netzer, and Piran (1990) have recently argued that relativistic effects close to the black hole reduce the polarization expected in the disk model to the observed value. However, since the accretion disk contributes substantially only to the ultraviolet light, and the ultraviolet polarization of BL Lac objects is not measured, the polarization expected from a disk places little constraint on the disk model. Future high-quality observations of the polarization in the UV and its variability are needed in order to constrain models like the present one.

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