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A MODEL FOR THE X-RAY AND ULTRAVIOLET EMISSION FROM SEYFERT GALAXIES AND GALACTIC BLACK HOLES

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ABSTRACT

We propose that the X-ray emission from radio-quiet active galactic nuclei and galactic black holes is due to Comptonization of soft thermal photons emitted by the underlying accretion disk in localized structures (blobs). The power per unit area produced by the blobs, impinging on the disk, can easily dominate the radiation internally produced by the disk. In this case the electron temperature and the high-energy spectrum can be determined in a similar way to that used in the previously studied homogeneous model (Haardt & Maraschi 1991). However, in the present model, (*a*) the emitted spectrum is largely independent of the *fraction* of gravitational power dissipated in the blobs; (*b*) the X-ray spectrum can be harder depending on a form factor of the blobs; (*c*) the UV (or soft X-ray for galactic objects) luminosity that is not intercepted by the blobs can be larger than the X-ray luminosity. In the framework of a simplified accretion disk α-Ω dynamo model, we make order-of-magnitude estimates of the number of active blobs, their size, their luminosity, and hence their compactness, finding values in agreement with what is observed. The expected UV to X-ray spectra and correlations of X-ray and UV light curves are discussed.

Subject headings: accretion, accretion disks — galaxies: Seyfert — plasmas — radiation mechanisms: thermal — X-rays: general

1. INTRODUCTION

The recent observations by the Oriented Scintillation Spectrometer Experiment (OSSE) on board the *Compton Gamma Ray Observatory* show spectral "breaks" or cutoffs in the hard X-ray spectra of some Seyfert 1 galaxies (e.g., Cameron et al. 1992; Maisack et al. 1993) supporting thermal or quasi-thermal models for the X-ray emission, in which a population of semirelativistic electrons Comptonizes the available soft photons (e.g., Shapiro, Lightman, & Eardly 1976; Pozdnyakov, Sobol', & Sunyaev 1983; Sunyaev & Titarchuk 1980), and reinforcing the analogy with the high-energy spectra of galactic black hole candidates (GBHs) (e.g., Done et al. 1992; Johnson et al. 1993; Grebenev et al. 1993).

A second implication of the OSSE observations is that the luminosity L_X in the medium and hard X-ray range can be reliably estimated. If the "X-ray bolometric correction" established for the few galaxies detected by OSSE is adopted as a general property, the ratios of X-ray to UV flux measured with *ROSAT* for a large sample of objects (Walter & Fink 1993) lead to an estimate of the X-ray luminosity in many cases definitely smaller than that at the UV bump, $L_{\rm UV}$. On the other hand, in the best-studied objects, the Seyfert galaxies NGC 4151 and NGC 5548, the UV and X-ray fluxes are comparable and vary in a correlated fashion on timescales of weeks (Perola et al. 1986; Clavel et al. 1992, hereafter C92). This led to the suggestion that in these objects the UV emission is due to reprocessing of the higher frequency radiation, implying $L_X \gtrsim L_{\rm UV}$.

We have proposed (Haardt & Maraschi 1991, 1993, hereafter Papers I and II, respectively) that the main features of the high-energy emission from radio-quiet active galactic nuclei (AGNs), and GBHs (Haardt et al. 1993; Ueda, Ebisawa, & Done 1994), can be explained by the interplay of a hot active corona with a colder accretion flow. Soft thermal photons with an energy of few tens (hundreds for GBHs) of electron volts are Comptonized by midly relativistic electrons in the hot corona, leading to the formation of a power-law spectrum with a high-energy cutoff. In steady state, the equilibrium temperature of the electron distribution (assumed to be Maxwellian) can be computed balancing heating and radiative cooling, and depends only on the electron scattering optical depth τ. Furthermore, when the compactness ℓ of the source (proportional to the luminosity-to-size ratio) is large, electron-positron pair production yields a lower limit to τ and an upper limit to the temperature kT. Quite remarkably, for $10 \lesssim \ell \lesssim 100$ the theoretical values 300 keV $\gtrsim kT \gtrsim$ 50 keV are close to the first results of the OSSE experiment (e.g., Maisack et al. 1993; Cameron et al. 1993).

The average observed X-ray spectrum can be reproduced if the ratio of the Comptonized to soft emission luminosities,

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L_C/L_S, is $\simeq 2$. In fact this value leads to a Compton y-parameter close to 1, and to a spectral index of the Comptonized spectrum $\alpha_x \simeq 1$. In Papers I and II the condition $L_C/L_S \simeq 2$ was achieved by assuming that the *entire* gravitational power is released in the hot corona. Therefore, the soft emission L_S is derived only from absorption and reprocessing of the high-energy flux impinging on the disk. In that model, roughly half of the Comptonized photons are absorbed in the cold disk and reemitted as thermal radiation, while half are radiated away. Any further local dissipation within the disk would produce additional soft photons, lowering the coronal temperature and hence giving rise to steeper X-ray spectra. The model is then tightly constrained, and predicts nearly equal UV and X-ray luminosities. As was illustrated in Paper II, the different angular distributions of the Comptonized photons with respect to the thermal ones can give rise to a UV flux larger than the X-ray flux for viewing angles close to face-on, but it seems difficult to achieve soft-to-hard ratios greater than 5. Another prediction is a tight correlation between the hard Comptonized photons (X-rays) and the soft photons emitted by the cold disk (UV or soft X-rays for GBHs). For NGC 4151 and NGC 5548, the UV and X-ray fluxes simultaneously observed in different periods are indeed correlated, but variations (up to 30%; Nandra et al. 1991) in X-rays on timescales of hours are not accompanied by similar variations in the UV. Furthermore, for large UV fluxes, the correlation between X-rays and UV breaks down (Perola et al. 1986; C92).

In Papers I and II we considered a uniform, plane-parallel model which allowed us to minimize the parameters of the problem. Here we wish to relax these assumptions and adopt a more physical description of the energy dissipation process in order to account for a broader set of observational results, including X-ray and UV variability.

We maintain the assumption that the disk magnetic field can drain a fraction f of the accretion power outside the accreting flow, but we assume that this power is dissipated in active localized blobs which cover a small fraction of the total disk area. In § 2 we discuss the effects of the new assumptions on the observed emission spectral shape. In § 3 we outline a plausible scenario that can lead to the formation of a structured corona, and we discuss a specific model following Galeev, Rosner, & Vaiana (1979, hereafter GRV). We also estimate the number of active blobs, their size, their luminosity, and hence their compactness. Finally, in § 4 we discuss our results, and in § 5 we present a brief summary of our results.

2. STRUCTURED CORONA: PHENOMENOLOGICAL APPROACH

We assume that the accretion disk dissipates internally a fraction $(1-f)$ of the accretion power Q (ergs cm^{-2} s^{-1}), while the remaining fraction f is stored in magnetic field structures which lead to active blobs of typical size R_b. We also assume that the energy is stored in the magnetic field in a "charge time" t_c but is released on a much shorter "discharge time" t_d. The ratio t_d/t_c clearly coincides with the fraction of the disk area which is covered by active blobs at any time. The luminosity of a single blob will be

$$L_{\rm blob} = \left(fQ\,\frac{t_c}{t_d}\right)\pi R_b^2\ . \qquad (1)$$

Assuming that roughly half of the blob luminosity is intercepted and reprocessed locally by the underlying disk, the total luminosity crossing the blob is

$$L_{\rm cool} = (Q_{\rm disk} + Q_{\rm rep})\pi R_b^2 = \left[(1-f)Q + 0.5CfQ\,\frac{t_c}{t_d}\right]\pi R_b^2\ . \qquad (2)$$

The parameter C indicates the fraction of reprocessed radiation which crosses the blob. In the plane-parallel limit $C = 1$, since the whole reprocessed flux is effective in cooling the corona, while a height-to-radius ratio for the blobs of order unity leads to $C \simeq 0.5$.

Writing the Compton amplification factor as $(A-1) = L_{\rm blob}/L_{\rm cool}$, we see that A is a function of three parameters, namely, f, C, and t_c/t_d. However, in the limit $f \gg t_d/t_c$ we have

$$(A-1) \simeq 2/C\ , \qquad (3)$$

and only C plays a role in determining the emitted spectrum. This condition means that the disk emission per unit area below the blobs is dominated by the reprocessed radiation originally emitted by the blobs themselves. If t_d/t_c is small, we can obtain the "right" α_x nearly independently of the value of f; large UV luminosities are thus possible even if the reprocessed radiation dominates the cooling of the blob. Since the ratio of the disk to the *observed* blob emission is $2(1-f)/f$, in principle f can be derived from observations.

The actual value of α_x is determined by C. In the geometrically thin case we have $C = 1$, and we obtain the results discussed in Papers I and II. If the blobs have a height-to-radius ratio of the order of unity or more, $C < 1$, the source is *photon-starved*, and the corresponding power-law spectral index is flatter. The observed spectrum is the superposition of the spectra of several different active blobs, all producing (in equilibrium) roughly the same slope.

Different models of the formation of active blobs can share the general features outlined above. Following GRV, we discuss a specific model below.

3. STRUCTURED CORONA: A SIMPLE MODEL

3.1. *Timescales*

It has been realized that the magnetic field can be amplified by differential rotation in accretion disks to equipartition values and can then provide the needed viscosity and energy dissipation mechanisms. A discussion of the different ways in which this could occur can be found in, e.g., the review of Heyvaerts (1990). Here we show that by adopting the simple model of GRV we can derive plausible values for the parameters introduced phenomenologically in the previous section, i.e., the ratio t_d/t_c and the size R_b of the blobs, as well as the number of active blobs at any time.

In the dynamo model of GRV, the disk differential rotation causes the azimuthal magnetic field B_ϕ to grow exponentially because of a feedback mechanism linking the radial and vertical components of the magnetic field $\boldsymbol{B}$ to B_ϕ. The magnetic field is amplified until its pressure equals the surrounding gas pressure, which leads to buoyancy of the magnetic flux tubes (see Stella & Rosner 1984). While reconnection of the magnetic field lines *within* the disk is ineffective in preventing the growth of the magnetic field, it probably occurs very rapidly in the much more tenuous coronal medium, transforming the stored energy in kinetic energy of fast particles. Within the disk, B_ϕ grows as $\dot{B}_\phi = (3v/R)B_\phi$, where the convection velocity v is $\approx \alpha^{1/3}\Omega z_0$. Here α is the parameter linking the stress tensor to the total disk pressure, $\Omega = (GM/R^3)^{1/2}$ is the Keplerian angular velocity, and z_0 is the disk scale height. We can then identify the charge timescale t_c with $R/3v$.

From the standard theory of accretion disks (Shakura & Sunyaev 1973), in the radiation-pressure–dominated region $z_0 \approx 9R_S \mathscr{L} S(r)$, where $\mathscr{L}$ is the total luminosity of the source in Eddington luminosity units, and $S(r) = 1 - (3/r)^{1/2}$. Here R_S is the Schwarzschild radius $R_S \equiv 2GM/c^2$, and $r \equiv R/R_S$. According to GRV, the size of the loops is $R_b \approx z_0/\alpha^{1/3}$. Note that, since $z_0 \propto \mathscr{L}$, the compactness ℓ of a single loop ($\propto L/R_b$) is independent of the source luminosity.

With the above estimates the charge timescale becomes

$$t_c \sim \frac{R}{3\alpha^{1/2}\Omega z_0} \sim 0.5\,\frac{r^{5/2}M_6}{\alpha^{1/3}\mathscr{L}S(r)}\ \mathrm{s}\,, \tag{4}$$

where $M_6 \equiv M/10^6\ M_\odot$. Note that in sources closer to the Eddington limit the magnetic field grows rapidly because of the higher convection velocity ($v \propto z_0 \propto \mathscr{L}$).

The discharge timescale t_d depends on the microphysical processes that cause the dissipation of magnetic energy. We parameterize it as

$$t_d = a\left(\frac{R_b}{c}\right). \tag{5}$$

Here t_d is the maximum of the time needed to transfer the magnetic energy to the particles and the cooling timescale of the particles. Since the cooling time is very short (see below), the strongest constraint derives from the acceleration timescale, which is highly uncertain but should be $\sim R_b/v_{\rm rec}$, where $v_{\rm rec}$ is the reconnection velocity. Theoretical estimates of $v_{\rm rec}$ range from $v_{\rm rec} \sim v_{\rm A}/\ln R_m$, where $v_{\rm A}$ is the Alfvén velocity and R_m is the magnetic Reynolds number for a Petschek-type reconnection (Petschek 1964), to $v_{\rm rec} \sim v_{\rm A}$ (Priest & Forbes 1986).

A rough estimate of a can be derived from the $\sim$10 s duration of the impulsive phase of solar flares during which particles are believed to be accelerated. Typical solar values of R_b and $v_{\rm A}$ are $\sim 10^9$ cm and $\sim 6 \times 10^8$ cm s^{-1}, respectively, so that the acceleration time is $\sim$6 times the Alfvén wave crossing time. Assuming that in the AGN rarefied coronal medium $v_{\rm A} \sim c$, we obtain $a \sim 6$. The ratio t_c/t_d can then be written from equations (4) and (5) as

$$\frac{t_c}{t_d} \sim 3\left(\frac{r}{5}\right)^{5/2}\left(\frac{10}{a}\right)\left(\frac{0.1}{\mathscr{L}}\right)^2\left[\frac{1}{S(r)}\right]^2, \tag{6}$$

independent of viscosity and mass. At $r = 5$ we obtain $t_c/t_d \gtrsim 60$ (for $\mathscr{L} \lesssim 0.1$), which ensures that $Q_{\rm rep} \gg Q_{\rm disk}$ throughout the disk. The ratio t_c/t_d becomes of order unity in the innermost part of the disk ($5 \lesssim r \lesssim 12$) only for sources radiating close to the Eddington limit.

Since the cooling time of the accelerated particles is shorter than the timescale of the energy release in the loops (see below), we can think of the spectral evolution as a succession of stationary states. The energy input in the hot particles may fluctuate strongly on the timescale associated with the evolution of magnetic structures in the loop phase (minutes to hours for Seyfert galaxies), while keeping a constant average on medium timescales (days), determined by the constancy in the energy transport of the accretion flow.

Using the timescale estimates given above, the loop variability timescale should be of the order of minutes for a $10^6\ M_\odot$ object, and of milliseconds for a 10 $M_\odot$ object (for a detailed discussion of variability in coronal models see also Pudritz 1981a, b; Pudritz & Fahlman 1982; Abramowicz et al. 1991).

3.2. *Number and Luminosity of Active Loops*

We assume that the dynamo process operates all over the disk. In a disk sector between $R - R_b$ and $R + R_b$ the number of magnetic loops that are growing *within* the disk is $N_{\rm grow} = 4R/R_b$, and the number of active loops *above* the disk is $N_{\rm act} = (t_d/t_c)N_{\rm grow}$. Transforming these two quantities into differentials, [i.e., $dN/dr = N/(2R_b)$], and substituting the values of t_c/t_d and R_b derived above, we obtain the differential number of active loops. Integrating from $3R_S$ to infinity, we then derive the total number of active loops at any time, that is, $N_{\rm tot} \sim 5a\alpha^{2/3}$. This number does not depend either on the luminosity or on the mass of the source.

According to Pringle (1981), observations of stellar accretion disks seem to require $\alpha \sim 0.1$. Setting $a = 10$, we find that $N_{\rm tot} \sim 10$. From simple Poissonian noise arguments, this is what is needed to explain X-ray fluctuations of a factor of $\sim$2 on short timescales, which are typically observed in AGNs and GBHs.

Finally the luminosity of a single blob located at r is estimated by

$$\begin{aligned} L_{\rm blob} &= fQ(R)2\pi R\,\frac{dR}{dN_{\rm act}} \\ &\sim 1.2 \times 10^{43} M_6\left(\frac{f}{0.2}\right)\left(\frac{10}{a}\right)\left(\frac{0.1}{\alpha}\right)^{2/3}\left(\frac{1}{r}\right)^{1/2} \\ &\qquad \times \mathscr{L}S(r)\ \mathrm{ergs\ s^{-1}}\,. \end{aligned} \tag{7}$$

Since $S(r) = 1 - (3/r)^{1/2}$, the most luminous blobs are those located at $r = 12$ (although the maximum of the coronal surface emissivity is at $r \simeq 5$) an can have 30% of the total luminosity emitted by the entire ensemble of loops. From the above equation, the compactness parameter of the loops is

$$\ell \sim 50\left(\frac{f}{0.2}\right)\left(\frac{10}{a}\right)\left(\frac{0.1}{\alpha}\right)^{1/3}\left(\frac{1}{r}\right)^{1/2}. \tag{8}$$

In the most radiative part of the disk the blobs have $\ell \sim 30$. This should be considered as a *lower limit* to the actual compactness, since the acceleration region may be smaller than R_b, the value used in the derivation of equation (8). The compactness ℓ is independent of the source luminosity and the mass of the central black hole. This may account for the remarkable similarity of the high-energy spectra of AGNs and GBHs. Furthermore, the order of magnitude of the compactness parameter is consistent with observations (Done & Fabian 1990). In retrospect, since the Compton cooling time in a source of compactness ℓ is $\sim(R/c)/\ell$, our assumption that the cooling time is shorter than the acceleration time is justified.

3.3. *Reprocessed Radiation*

The temperature of the thermal radiation below the loops will be generally higher than the temperature of the disk emission at the same radius producing a hotter thermal component superposed on the multicolor disk emission. The flux per unit time per unit area of the reprocessed radiation below the loops is a factor t_c/t_d higher than that due to viscous dissipation in the disk. Using a blackbody approximation, the temperatures of the two components can be written as

$$kT_{\rm disk} \sim 30 M_6^{-1/4}(1-f)^{1/4}\left(\frac{5}{r}\right)^{3/4}\left(\frac{\mathscr{L}}{0.1}\right)^{1/4} S(r)^{1/4}\ {\rm eV}\ , \quad (9a)$$

$$kT_{\rm rep} \sim 35 M_6^{-1/4} f^{1/4}\left(\frac{10}{a}\right)^{1/4}\left(\frac{5}{r}\right)^{1/8}\left(\frac{0.1}{\mathscr{L}}\right)^{1/4} S(r)^{-1/4}\ {\rm eV}\ . \quad (9b)$$

In the innermost part of the accretion disk, the reprocessed component can be $\approx$2–3 times hotter than the disk temperature at the same radius. The reprocessed radiation temperature is a very weak function of the radius and is higher in low-luminosity objects. The total thermal emission from the accreting flow is then formed by a multicolor spectrum as in the standard α-disk (Shakura & Sunyaev 1973)—with the difference that at each R the surface emissivity is a fraction $(1-f)$ of that of a standard disk—plus a hotter multicolor component with a much smoother radial dependence.

4. DISCUSSION

We have proposed that the formation of a structured corona above an accretion disk can be responsible for the X-ray emission of AGNs and GBHs. The patchy structure of the corona can be due to the formation of magnetic loops in which the energy is stored over a long "charge" time and is subsequently released (e.g., by reconnection) over a much shorter "discharge" time. Each blob can then produce X-rays in the same way as the homogeneous corona discussed in Papers I and II, but, at the same time, the present model can account for a broader set of observational constraints.

The model includes three emission components: (1) the luminosity due to dissipation within the accretion disk, which we generally call $L_{\rm UV}$ (although in GBHs it is mostly emitted in the soft X-ray band); (2) the upward Comptonized luminosity L_X extending from the medium to the hard X-ray range; and (3) the reprocessed luminosity $L_{\rm rep}$, which comprises a thermal peak hotter than the direct disk emission and a Compton reflection hump at 10–100 keV (Lightman & White 1988).

The ratio of L_X to $L_{\rm UV}$ is determined by the fraction f of the total gravitational power stored in the magnetic field, while $L_{\rm rep}$ is *always* of the order of L_X. Observations of Seyfert galaxies suggest that the UV emission may be up to an order of magnitude larger than the X-ray emission (e.g., Walter & Fink 1993): in the present model this corresponds to $f = 0.2$. For $f = 0.2$ the high-energy spectrum can have a spectral index close to unity if $t_c/t_d \gg 5$, which is not a severe constraint.

The reprocessed component $L_{\rm rep}$ may be related to the variable hard UV component inferred in some Seyfert galaxies (e.g., NGC 4151) and/or to the so-called soft excess observed in the soft X-ray band (e.g., Yaqoob & Warwick 1991; Pounds et al. 1994; Walter et al. 1994). The soft-excess luminosity relative to the direct disk emission $L_{\rm UV}$ is determined by f.

The actual size scale and number of active regions, and the associated variability timescales, estimated in § 3 on the basis of the GRV model for the magnetic corona, are generally consistent with observations. In particular, the number of blobs turns out to be $\sim$10, independent of the luminosity of the source and of the mass of the central black hole. Short-timescale variability can be associated with stochastic noise in the number of active blobs which can easily produce flux variability up to a factor of 2. Since the size of the blobs scales with total luminosity L, the variability timescale turns out to be proportional to L.

L_X can fluctuate on the shortest timescales, and its fluctuation is associated with the blob size and the energy dissipation rate. $L_{\rm rep}$ must vary in a correlated fashion with L_X. However, a smearing in time can result from the shape of the blobs which may illuminate a larger area than that intercepted by the blobs themselves ($C < 1$; § 2). In addition, there is a dilution introduced by the disk component $L_{\rm UV}$. In objects where the UV component is definitely more luminous than the X-ray component ($f \ll 1$), the dilution is expected to be important. In these cases we do not expect correlated variability on short timescales between the UV and the X-rays. However, the correlation could hold on medium timescales if the power dissipated in the disk varies and f is constant. On the other hand, we predict a substantial amount of UV flux correlated to the X-rays in sources where these two components have comparable luminosity. We note that in the two cases where the UV–X-ray correlation has been observed, NGC 5548 (C92) and NGC 4151 (Perola et al. 1986; Perola & Piro 1994), the UV and X-ray fluxes are indeed comparable. It is therefore possible, pending an estimate of the bolometric correction factors for the two bands (e.g., Perola & Piro 1994), that for these objects f is close to unity and therefore the reprocessed component is strong in the UV. The lack of short time variations in the UV (C92) suggests that the reprocessing region is greater than the size of the blobs. This is consistent with a moderate photon starvation of the emitting blobs (i.e., $C < 1$), as required by the flatness of the 2–20 keV spectrum of these two objects ($\alpha_x \simeq 0.5$ for NGC 4151 [Yaqoob & Warwick 1991] and $\alpha_x \simeq 0.8$ for NGC 5548 [Nandra et al. 1991]).

We note that more reprocessing of the emitted radiation can occur in other regions farther away from the central black hole, like the intermediate accretion disk, the broad-line clouds, and the obscuring torus. A discussion of such mechanisms is beyond the scope of this *Letter*.

5. SUMMARY

Our results can be summarized as follows:

1. In the limit $f \gg t_d/t_c$, the ratio between the Comptonized luminosity and the luminosity injected in soft photons in each blob is independent of f, i.e., the fraction of gravitational power carried by the magnetic field. This ensures that the spectral index of the Comptonized component is largely independent of details, and different blobs produce spectra with the same power-law index. The ratio $L_{\rm UV}/L_X$ can be large in the present model, since not all the accretion power is assumed to be released in the hot corona (cf. Papers I and II).
2. The number and compactness of active blobs are independent of the source luminosity and of the central black hole mass.
3. The actual value of the X-ray spectral index is controlled by the geometry of the blobs. Quasi-spherical blobs will be photon-starved, producing flatter spectra and a smearing of the reprocessed component in space and time.
4. Short-term variability of the X-ray luminosity can be associated with the stochastic noise in the number and luminosity of active blobs. A reprocessed component with temperature higher than the disk emission and with luminosity similar to the X-ray luminosity is predicted to follow the X-ray variations with some smearing on the shortest timescales.

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