X-rays From Magnetic Flares In Cygnus X-1: A Unified Model With Seyfert Galaxies

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ABSTRACT

Some recent work, e.g., by Zdziarski et al., has shown that the spectrum of Seyfert 1 Galaxies is very similar to that of several Galactic Black Hole Candidates (GBHCs) in their hard state. However, the smallness of the observed reflection component in Cygnus X-1, in addition to other constraints, seem to rule out the two-phase model (otherwise successful in the case of Seyfert Galaxies) for GBHCs. Here, we show that the latter conclusion is based on a number of key assumptions about the X-ray reflection/reprocessing within the cold disk that probably are not valid when the overlying corona is patchy, e.g., when it is comprised of localized magnetic flares above the disk. We find that if the X-rays are emitted within these magnetic structures atop the cold disk, then the X-ray reflection/reprocessing of the primary X-rays by the latter is not scale-invariant with respect to the black hole mass. In particular, we show that in GBHCs the energy deposited by the X-rays cannot be re-radiated fast enough to maintain equilibrium, unless the X-ray skin heats up to the Compton temperature, at which point the gas is mostly ionized. This leads to a substantially reduced cooling rate for the active regions due to the correspondingly smaller number of re-injected low-energy photons. We model this effect by introducing a transition layer situated between the corona and the cold disk, and find that the resulting spectrum is harder than that obtained with the standard (and unrealistic) two-phase model. We apply this model to Cygnus X-1 and show that it can account for its observed spectrum. This analysis therefore seems to provide a consistent picture for both Seyfert Galaxies and GBHCs within the same framework, with differences arising due to the changing physical conditions in the two categories of sources, rather than due to an ad hoc variation of the model parameters.

Subject headings: accretion disks — black hole physics — Cygnus X-1 — galaxies: Seyfert — magnetic fields — radiative transfer

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1. Introduction

The progress made in recent years in understanding the X-ray spectra of Seyfert Galaxies and Galactic Black Hole Candidates (GBHCs) indicates that the reflection and reprocessing of incident X-rays into lower frequency radiation is an ubiquitous and important process. For Seyfert Galaxies, the X-ray spectral index hovers near a “canonical value” ($\sim 0.95$; Pounds et al. 1990, Nandra & Pounds 1994; Zdziarski et al. 1996), after the reflection component has been subtracted out of the observed spectrum. It is generally believed that the universality of this X-ray spectral index may be attributed to the fact that the reprocessing of X-rays within the disk-corona of the two-phase model leads to an electron cooling rate that is roughly proportional to the heating rate inside the active regions (AR) where the X-ray continuum originates (Haardt & Maraschi 1991, 1993; Haardt, Maraschi & Ghisellini 1994; Svensson 1996). Nayakshin & Melia (1997a) have considered the physical conditions inside the localized ARs, and showed that the ARs are probably magnetically dominated structures, i.e., magnetic flares (see also Haardt et al. 1994; Galeev, Rosner & Vaiana 1979).

GBHCs have similar, though considerably harder, spectra and a reflection component less prominent than that of Seyfert Galaxies (Zdziarski et al. 1996). Indeed, Rossi X-ray observations of Cygnus X-1 show no significant evidence for a reflection component (Dove et al. 1997a). For this reason, among others, Dove et al. (1997a, b), Gierlinski et al. (1997) and Poutanen, Kroll & Ryde (1997) have concluded that the two-phase model (i.e., the model in which the X-rays are created by localized ARs above the cold accretion disk) is not a suitable explanation for the observed spectrum of Cygnus X-1. The harder spectrum of GBHCs requires a much lower cooling rate than can be expected in the two-phase model. However, as we shall show below, this conclusion relies heavily on the assumption that the reflection/reprocessing process in the GBHCs is similar in nature to that of the higher mass Seyfert nuclei. In view of the fact that in most situations the accretion disk physics is scale-invariant, this at first appears to be a reasonable assumption (but see Ross, Fabian & Brandt 1996).

In this Letter, we point out that previous studies of the X-ray reflection (e.g., Sincell & Krolik 1997; Magdziarz & Zdziarski 1995; and additional references cited in Nayakshin & Melia 1997b) have concentrated on a static, full corona, a model that is unlikely to work even for Seyfert Galaxies (e.g., Haardt et al. 1994; Svensson 1996; Nayakshin & Melia 1997a). Motivated by this fact, Nayakshin & Melia (1997b; hereafter paper I) investigated the X-ray reflection process in AGNs assuming that the ARs are magnetic flares above the disk. These flares are short lived (see below), and the properties of the transient X-ray reflection turn out to be similar, and yet different enough from the static reflection process to provide an interesting explanation for the narrow range in the observed temperature of the Big Blue Bump and the low degree of ionization in the underlying disk.

It is therefore important to consider the physics of reflection in the two-phase model for GBHCs with transient ARs, paying particular attention to aspects of this process that are not scale-invariant with respect to the black hole mass. Below we show that a transient X-ray irradiation of the disk may account for the differences in the reflected fraction and the overall spectrum of Seyfert Galaxies and GBHCs. We find that the X-ray skin in GBHCs is much hotter and more strongly ionized than that in Seyfert nuclei, and is probably at the local (optical depth dependent) Compton temperature. It therefore acts as a “transition” layer in the case of GBHCs. This is in contrast to the situation in static X-ray reflection models, where the pressure equilibrium condition in this skin is black hole mass-invariant and leads to a cooler and far less ionized plasma.

As we shall see, the reflection process in a transition layer held at the Compton temperature substantially reduces the Compton cooling rate within the corona due to the upscattering of reprocessed radiation. This is due to the fact that a fraction of the hard X-ray photons incident on this layer are reflected back before they can reach the cooler accretion disk material, where reprocessing of these photons into softer ($kT \sim 100$ eV) radiation takes place. We present several test results indicating that the presence of this transition layer, heated and cooled by Compton scattering with the hot coronal and cold disk radiation leads to a spectrum that is much steeper than that of the standard two-phase model. Our results demonstrate that a consideration of the structure of the X-ray skin in a realistic two-phase model may therefore remove many current inconsistencies of the coronal picture with observations. We point out that the two-phase model with magnetic flares as the particle energizing mechanism in active regions may consti-
stitute a single explanation for both Seyfert nuclei and GBHCs, and account for differences in their spectra self-consistently.

2. Transient X-ray Reflection For GBHCs

As shown in paper I, the main characteristic of transient reflection, distinguishing it from its well-studied static counterpart, is that magnetic flares can only be active during a disk hydrostatic time scale. It is not difficult to show (e.g., using the model of Svensson & Zdziarski 1994) that the photon diffusion time across the disk is much longer than this for both radiation and gas-dominated disks. Therefore, no thermal equilibrium can be established between the underlying cold disk and the incident X-radiation. Instead, a quasi-equilibrium is established within an X-ray skin with Thomson optical depth \( \tau_T \sim \tau \). It is this X-ray skin that plays the major role in reprocessing and reflecting the incident X-rays.

Under the very intense incident X-ray flux, the upper layer of the disk in Seyfert nuclei contracts to a high density, which allows the irradiated gas to emit the deposited energy efficiently due to the strong density dependence of the optically thin free-free process (e.g., Rybicki & Lightman 1979). However, as was noted in paper I, this treatment is valid only when the X-ray skin is optically thin to free-free emission. Using a Rosseland mean free-free optical depth and Equation (4) of Nayakshin & Melia (1997a), it is straightforward to see that the free-free optical depth of the X-ray skin is \( \tau_{HF} \simeq 5 \times 10^{-5} \left( \tau_T / 3 \right)^2 l_2^2 \Delta R_{13}^{-1/2} T_6^{-7/2} \), where \( l_2 \equiv 1 / 100 \sim 1 \) is the compactness parameter of the AR, \( T_6 \) is the electron temperature in units of \( 10^6 \) Kelvin, and \( \Delta R_{13} \equiv \Delta R / 10^{13} \) cm is a typical size of the AR, expected to be of the order of the disk scale height. In Seyfert nuclei, \( \tau_{HF} \) is very much smaller than unity, validating the optically thin approximation. However, rescaling the parameters for the case of GBHCs with a mass \( \sim 10 M_\odot \), we obtain

\[
\tau_{HF} \simeq 500 \times \left( \tau_T / 3 \right)^2 \frac{l_2^2}{\Delta R_6} T_6^{-7/2}. \tag{1}
\]

With contributions from both the gas and the reprocessed radiation, which was neglected in paper I. The physical conditions in the X-ray skin of Seyfert nuclei are such that the internal gas and radiation pressures are comparable, but in an optically thick skin in GBHCs the radiation pressure would be dominant since a typical photon suffers many absorption events before escaping from the gas. To see this, we note that the internal radiation pressure must be smaller than the external X-ray pressure, so that

\[
\tau F_{HF}/c \lesssim F_x/c \tag{2}
\]

where \( F_x \) is the incident X-ray flux from the AR and \( \tau \) is the total optical depth of the X-ray skin. On the other hand, if the energy is reradiated by free-free emission, one should expect that

\[
2F_{HF} \sim F_x, \tag{3}
\]

where the factor 2 arises because the free-free radiation can escape in both the upward and downward (i.e., toward the disk midplane) directions. Thus, unless \( \tau \lesssim \tau_T \), a self-consistent equilibrium is not possible.

So what does happen in the irradiated layer? The incident X-rays, being too energetic (most of the flux in Cygnus X-1 is at \( > 20 \) keV), are not absorbed via free-free absorption if the gas temperature is \( T \ll \) few keV. Under these conditions, the X-rays would penetrate unimpeded into the skin to a Thomson optical depth \( \ll \) few, just as in the static case. Accordingly, irrespective of how large \( \tau_{HF} \) is, the incident X-rays would heat the upper region of the disk with \( \tau_T \ll \) few. However, the down-scattered X-rays, and the UV to soft X-ray photons due to internal emission would be readily absorbed and could not escape fast enough from the X-ray layer. The reprocessed radiation would build up inside the X-ray skin until it exceeded the external X-ray ram pressure, at which point the X-ray skin would expand, becoming hotter and less dense. Correspondingly, the free-free emissivity would drop, and the X-ray skin could not keep up with the energy deposition rate based solely on free-free processes. Perhaps the skin could cool by (i) mechanical motions of the gas, (ii) a downwards thermal conduction of the energy, or (iii) some form of magnetic or acoustic waves. However, these may be ruled out on the grounds that in order for a “non-radiative” cooling mechanism to keep up with the X-ray heating rate, the sound speed and/or the Alfvén
speed need to be as high as \(c\), whereas the gas maximum (i.e., the Compton) temperature is only about 15 keV for a typical GBHC hard state spectrum. At the local Compton temperature, the radiation field does not transfer any net energy to the gas by inverse Compton interactions.

As a result of the intense and transient X-irradiation in GBHCs, the X-ray skin thus heats to the Compton temperature, at which point it reflects many of the incident X-rays, rather than absorbing and reprocessing them. This contrasts with the static case, in which the nature of the pressure equilibrium within the X-ray skin is quite different (Sincell & Krolik 1997). Here, the transient illuminating X-ray flux \(F_x\) is much larger than in the static case, because the same fluence (i.e., integrated flux) must now be produced from a smaller coronal region and, in addition, the ARs are only active for a short time. Taken together, these lead to a larger ionization parameter \(\xi\), which is very large, and the GBHC X-ray skin is therefore in the “limit of a hot medium” (see §3.1 of Zycki et al. 1994). Since \(P_{\text{gas}}\) is certainly smaller than \(F_x/c\), \(\xi\) is very large, and the GBHC X-ray skin is therefore in the “limit of a hot medium” (see §3.1 of Zycki et al. 1994). The fact that this segment of parameter space is unlikely to be reached in a static corona is probably the reason why the spectroscopic consequences of reflection in a Compton equilibrium medium have not been considered earlier. We take up this question in the following section.

3. “Three-Phase” Model

Hereafter, we shall assume that the X-ray skin attains its local Compton temperature. We conduct several representative tests which will allow us to understand the important physics of the model, without necessarily attempting yet to fit any particular spectrum of a GBHC. Our model consists of an active region above the (heated) transition layer. The geometry of the AR is probably closer to a hemisphere than a slab, but for simplicity we shall adopt the latter for the radiation transport, neglecting the boundary effects. However crude, this approximation is adequate for our purposes. Experience has shown that spectra produced by Comptonization in different geometries are usually qualitatively similar (i.e., a power-law plus an exponential roll-over), and it is actually the fraction of soft photons entering the corona that accounts for most of the differences in the various models, because it is this fraction that affects the AR energy balance. We will therefore take the correct energy balance into account by assuming that the observed spectrum consists of the direct component, emerging through the top of the corona, and a fraction \(\Omega\) of the reflected radiation emerging from the transition layer. A fraction \(a = 0.5\) of the reflected spectrum goes back into the corona through its bottom (cf. Poutanen & Svensson 1994).

Below the transition layer lies an optically thick portion of the disk with Thomson optical depth \(\tau_T \gg 1\), held at a temperature \(T_{\text{bb}} = 100\) eV. We employ the Eddington (two-stream) approximation for the radiative transfer in both the AR and the transition layer, using both the zero (isotropic) and first order moments of the exact Klein-Nishina scattering kernel (Nagirner & Poutanen 1994). The optical depth of both the transition layer \(\tau_{\text{trans}}\) and the corona \(\tau_c\) are treated as parameters; \(\tau_c\) is fixed at an arbitrarily chosen value of 0.7 for the purpose of demonstrating the main point. In a generally accepted setup for the two-phase model, the transition layer is absent, and the X-rays incident on the cold disk below the AR are partially reflected (10 – 20%), while the rest are reprocessed and re-radiated as blackbody radiation. In the tests reported here, the same boundary condition is assumed between the cold disk and the transition layer. The radiation flux entering the cold disk from the transition layer is assumed to be reflected and reprocessed in the standard manner (Zdziarski et al. 1995), and then re-enters the transition layer. We assume a coronal heating rate much exceeding the local intrinsic disk flux and find the radiation field and the self-consistent temperature in both the corona (assumed to be uniform throughout the AR) and in the transition layer as a function of the optical depth.

Figure 1 shows the “observed” spectrum for several values of \(\tau_{\text{trans}}\): 0, 0.6, 2.5, and 10, with \(\Omega = 0.5\). It can be seen that the spectrum hardens as the optical depth of the transition layer increases. To help explain why this happens, we plot in Figure 2 the integrated albedo \(a\) for photons with energy \(E > 1\) keV as a function of \(\tau_{\text{trans}}\). The albedo is simply the inverse ratio of the incident flux in the given energy range to the returning one, i.e., that emerging from the top of the transition layer. As the transition layer optical thickness increases, a large fraction of the photons from the AR are reflected before they have a chance to penetrate into the cold disk where the blackbody component is created. Therefore, a
smaller flux of energy is deposited below the transition layer, which leads to a decreased cooling from the Comptonization of soft, reprocessed radiation. For a moderate optical depth \( \tau_{\text{trans}} \), this result is quite insensitive to the temperature in the transition layer as long as Fe is highly ionized. We checked this by simply setting the transition temperature at the arbitrarily chosen values of 1.5 and 6 keV, instead of the self-consistent temperature distribution calculated above, which varied from about 2 to 4 keV for the respective values of \( \tau_{\text{trans}} \). We found that the relative variations in the spectrum and the albedo resulting from this were less than about 3%. For higher optical depths \( (\tau_{\text{trans}} \gtrsim 4) \), pre-Comptonization of the soft disk radiation becomes important and additionally decreases the Compton cooling of the corona by this component. It is at these values of \( \tau_{\text{trans}} \) that the temperature of the transition layer becomes essential.

Figure 3 shows the observed spectrum (solid curve), comprising the intrinsic AR spectrum (short-dash) and the reflected component (emerging from the top of the transition layer; dotted curve) multiplied by \( \Omega = 0.5 \). Also shown is the reprocessed component at the base of the transition layer (long-dash). All the intensities propagate in the upward direction. Notice that due to the presence of the transition layer, the reflected component is much harder than the reprocessed component, which would be the “normal” reflection/reprocessing component without this layer. Notice also that the bump around \( \sim 40 \) keV normally attributed to the reflected component is broad (compared with the long-dashed curve), and so the reflected component is here less noticeable. Furthermore, the combined power below 2 keV accounts for only 25% of the total, whereas the corresponding fraction is about 50% in the standard (static) two-phase model.

4. Discussion

By considering time-dependent magnetic flares above a cold accretion disk, we have shown that the gas density within the X-irradiated skin of GBHCs is smaller than expected on the basis of a simple rescaling of the transient X-ray reflection process in Seyfert nuclei (paper I). The lower density significantly decreases the efficiency of free-free emission and the layer cannot cool, leading instead to a transition region at the Compton equilibrium temperature (typically a few keV). As a result, most of the incident X-rays are Compton reflected back into the AR before reaching the cooler disk material where reprocessing into a soft-excess component occurs. Accordingly, the amount of cooling due to the soft radiation re-entering the AR is drastically reduced and this allows the two-phase model with magnetic flares to reach the parameter space necessary to explain the observed X-ray spectrum of Cygnus X-1.

The consequences of this “three-phase” structure include the following: (1) GBHCs spectra should be harder than those in typical Seyfert 1s. For \( \tau_{\text{trans}} \gg 1 \), the spectrum may be somewhat different from that of single cloud Comptonization plus a reflection component, especially in the region of \( \sim 30 - 200 \) keV (see Fig. 3 and Gierlinski et al. 1997). (2) The observed soft X-ray excess should contain comparatively less power than the hard component, in contrast to Seyfert 1s. (3) The Thomson optical depth of the flares should be similar in the GBHCs and Seyfert Galaxies, and therefore so should the electron temperature within their ARs (see Nayakshin & Melia 1997b; this aspect of the model does not depend on the black hole mass). (4) No anisotropy break should be seen in the spectrum due to the input “soft” radiation not being a blackbody and entering the ARs sideways (in accordance with observations; see, e.g., Gierlinski et al. 1997). (5) The reflected component in the observed spectrum must be less pronounced or not observable, depending on the transition layer optical depth. (6) The Fe lines from the inner accretion disk should be either weak or broad and thus indistinguishable from the continuum due to Comptonization within the transition layer. (7) The same is true for the Fe edge. (8) X-ray variability should be observed on a time scale of the order of the disk hydrostatic time scale, i.e., \( \sim \) milliseconds. All these features appear to be consistent with the observed characteristics of Cygnus X-1. This picture therefore holds promise in removing several deficiencies of the static and unphysical simple two-phase model, which has already been ruled out (Dove et al. 1997a,b; Gierlinski et al. 1997; Poutanen et al. 1997a,b).

Although a more detailed spectral modeling is needed to confirm many of these predictions for the hard state spectrum in GBHCs, even the simple treatment used here shows that the two-phase model with magnetic flares as ARs may ultimately account for both the characteristics of Seyfert Galaxies (Nayakshin & Melia 1997a; and references cited therein), and GBHCs. Very importantly, it explains the dif-
ferences in the spectra of these two classes of objects self-consistently, i.e., based solely on the physics of the irradiated region at the surface of the disk, rather than as a result of an \textit{ad hoc} variation of the parameters.

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Fig. 1.— Dependence of the “observed” spectra on the transition layer optical depth, $\tau_{\text{trans}}$, marked above corresponding curves.

Fig. 2.— Integrated albedo (reflected fraction) for photons with energy $> 1$ keV as a function of the transition layer optical depth. Also plotted (dotted curve) is the ratio of the hard observed luminosity (above 2 keV) to the total observed luminosity. Note that transition layer reflects more photons as $\tau_{\text{trans}}$ increases, and the spectrum becomes harder.

Fig. 3.— Decomposition of the observed spectrum (solid line), on the intrinsic AR spectrum (short-dashed) plus the reflection component (emerging from the top of the transition layer; dotted curve) multiplied by $\Omega = 0.5$. The reprocessed component at the base of the transition layer is also shown by the long-dashed curve. See text for discussion.
Figure 1

\[ \tau_{\text{trans}} = 10 \]

![Graph of E F(E) vs. Photon Energy (keV)](image)
Figure 2

\[ \frac{F_h}{(F_h + F_s)} \]

Albedo (E > 1 keV)

\[ \tau_{\text{trans}} \] (transition layer Thomson depth)
