THERMAL X-RAY LINE EMISSION FROM ACCRETING BLACK HOLES

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ABSTRACT

We present model X-ray spectra of accreting black holes with hot advection-dominated accretion flows, paying attention to thermal emission lines from the hot plasma. We discuss the emission-line diagnostics that are potentially observable with the next generation of X-ray observatories, emphasizing the possibilities for determining the outer radius of the hot plasma, the presence of a wind, and the relative importance of photoionization. We present example spectra of V404 Cyg in quiescence, the Galactic center black hole Sagittarius A*, and the nucleus of M87.

Subject headings: accretion, accretion disks — black hole physics — galaxies: nuclei — Galaxy: center — radiation mechanisms: thermal — X-rays: stars

1. INTRODUCTION

Some of the most important X-ray sources in the sky are accreting black holes. Examples are stellar mass black holes in X-ray binaries and supermassive black holes in the nuclei of our Galaxy and in the nuclei of other galaxies. X-ray emission from these sources arises through many processes: optically thick thermal radiation from an accretion disk (cf. Tanaka & Shibazaki 1996), Compton scattering of soft photons by a hot, optically thin plasma, either in a corona (see, e.g., Haardt & Maraschi 1991) or in an advection-dominated accretion flow (ADAF; Narayan & Yi 1994, 1995; Abramowicz et al. 1995; see Narayan, Mahadevan, & Quataert 1998b and Kato, Fukue, & Mineshige 1998 for reviews), and thermal bremsstrahlung from hot low-density gas. The continuum spectral energy distributions corresponding to these processes have been studied by a number of authors (see Liang 1998 and Mushotzky, Done, & Pounds 1993 for reviews).

Fewer models are available for X-ray line emission. Fluorescent line emission from cool gas irradiated by a hot corona has been studied in some detail (Mushotzky et al. 1993; Tanaka et al. 1995), but thermal X-ray line emission from hot, optically thin gas around black holes has not been discussed very much. We show that black holes that accrete via ADAFs with relatively low mass accretion rates might produce X-ray lines of sufficient strength to be detected with the upcoming X-ray missions. These lines will provide new constraints on the accretion flows in these systems.

We point out three significant diagnostic possibilities. First, the equivalent widths of the emission lines increase with the size of the ADAF region. Second, for a given ADAF size, the equivalent widths are much larger for models that include a wind than for models with no wind. And, third, photoionization is unimportant in an ADAF, while it dominates in some accretion disk corona models.

2. ADAF MODELS

ADAF models are Compton dominated when the mass accretion rate is high. If the Eddington-scaled accretion rate, \( \dot{m} = M/2.2 \times 10^{-3} m_\odot \text{yr}^{-1} \) (where \( M \) is the black hole mass in solar units), is close to a critical value, \( \dot{m}_{\text{crit}} \approx 0.05-0.1 \) (Esin, McClintock, & Narayan 1997), the Comptonization of soft photons (either from an outer disk or from thermal synchrotron emission) is strong and greatly exceeds the thermal emission. Thermal lines will therefore have low equivalent widths.

As the mass accretion rate decreases to \( \dot{m} \approx 0.01 \), thermal bremsstrahlung becomes relatively more important (Esin et al. 1997); the thermal lines that we are interested in should then have measurable equivalent widths. The electron temperature in an ADAF varies roughly as \( T_e \sim 10^{12} \text{K}/r \) for \( r \approx 10^7 \) (Narayan & Yi 1995), where \( r \) is the radius in Schwarzschild units (2.95 \( \times 10^7 m \text{cm} \)). Since the strongest X-ray line emission arises for \( T_e \sim 10^7-10^8 \text{K} \), the region of the flow between \( r \sim 10^4 \) and \( 10^5 \) is most important for our purpose. ADAFs can extend to such large radii for low \( \dot{m} \) only (Narayan & Yi 1995; Narayan et al. 1998b), which is another reason to concentrate on low-\( \dot{m} \) systems.

We have computed ADAF models and X-ray spectra of the following three low-\( \dot{m} \) systems: the X-ray binary V404 Cyg in quiescence, the Galactic center source Sagittarius A*, and the nucleus of the galaxy M87. The methods are described in Quataert & Narayan (1998 and references therein). There is some uncertainty in these models because of possible winds (Narayan & Yi 1994; Blandford & Begelman 1999; Quataert & Narayan 1998). Therefore, for each of our three systems, we have computed two models, one in which there is no wind (referred to as NW; the accretion rate \( \dot{m} \) is taken to be independent of radius) and one with a moderately strong wind (referred to as W; \( \dot{m} \) is assumed to vary with radius as \( r^{-0.9} \)). These two models probably bracket the true situation. We assume that in the NW model, electrons receive only a fraction, \( \delta = 0.1 \), of the viscously dissipated heat in the accretion flow, while in the W model, we set \( \delta = 0.3 \) (see Quataert & Narayan 1998). We assign reasonable values to the other microscopic parameters: viscosity parameter \( \alpha = 0.1 \), plasma \( \beta = 10 \). The results are not very sensitive to these values.

The system-specific parameter values are as follows (see Narayan, Barret, & McClintock 1997 for a compilation of the data on V404 Cyg, Narayan et al. 1998a for Sgr A*, and Reynolds et al. 1996 for M87). The black hole masses are \( m = 12 \) \((\text{V404 Cyg}), \ m = 2.5 \times 10^6 \) \((\text{Sgr A*}), \) and \( m = 3 \times 10^9 \) \((\text{M87})\), the distances are \( 3.5 \text{kpc} \) \((\text{V404 Cyg}), \ 8.5 \text{kpc} \) \((\text{Sgr A*}), \) and \( 16 \text{Mpc} \) \((\text{M87})\), and the absorbing columns are \( N_H = 1.1 \times 10^{22} \text{cm}^{-2} \) \((\text{V404 Cyg}), \ N_H = 6 \times 10^{22} \text{cm}^{-2} \) \((\text{Sgr A*}), \) and \( N_H = 2.5 \times 10^{20} \text{cm}^{-2} \) \((\text{M87})\); this \( N_H \) includes only the contribution of our Galaxy. We fitted \( \dot{m} \) in each model so as to reproduce the observed X-ray flux: \( \dot{m} = 0.0010, 0.0060 \) (NW...
and W models of V404 Cyg), 0.000070, 0.00024 (Sgr A*), and 0.0010, 0.011 (M87). For the W models, the values of $m$ refer to the outer edge of the ADAF.

The size of the ADAF region is uncertain. In V404 Cyg, the ADAF is believed to extend from the black hole horizon ($r = 1$) to a transition radius $r_\text{tr}$, beyond which the flow consists of a thin disk plus a corona. We take $r_\text{tr} = 10^{-4}$, as indicated by the width of the Hα line from the outer disk (Narayan et al. 1997). In the coronal region of this source, we set $m \propto r_\text{tr}/r$ to model the evaporation of hot gas from the disk into the corona (cf. Esin et al. 1997). In Sgr A*, there is no evidence of an outer disk, so we consider a pure ADAF model extending from $r = 1$ to an outer radius $r_\text{out}$. The stars whose winds supply most of the accreting mass (cf. Coker & Melia 1997) are located at $r \approx$ few time $10^5$. We therefore set $r_\text{out} = 10^5$. For simplicity, we use the same $r_\text{out}$ for M87.

### 3. MODEL X-RAY LINE SPECTRA

Each quasi-spherical ADAF model gives the electron density $n_e$ and electron temperature $T_e$ as a function of $r$ on a radial grid with ten zones per decade of $r$. Figure 1 shows these quantities for the NW and W models of Sgr A*.

For calculating the line spectrum, we divide the flow into an inner region from $r = 1$ to $10^4$ and an outer region beyond $10^5$. We compute the continuum emission from the inner region because of synchrotron emission, bremsstrahlung, and Comptonization, but we do not compute line emission; this is reasonable since the temperature is greater than $10^9$ K (Fig. 1), and the astrophysically abundant elements are fully ionized. In the outer region, we compute the line emission and thermal continuum in detail, but we do not consider either synchrotron emission or the effect of Comptonization; these latter processes are steep functions of the temperature and are negligible outside $r = 10^5$. We ignore any emission by the wind.

The spectral calculation in the outer region employs an extended version of the Raymond & Smith (1977) X-ray code to compute the bremsstrahlung, recombination, and two-photon continua and the emission in spectral lines. It computes the photoionization rate for calculating the ionization state. For the present models, we are mostly concerned with H-like and He-like ions. Collisional excitation (see, e.g., Pradhan, Norcross, & Hummer 1981 and Pradhan 1985), recombination to excited levels (see, e.g., Mewe, Schrijver, & Sylwester 1980), and dielectronic recombination satellite lines (see, e.g., Dubau et al. 1981 and Bely-Daubau et al. 1982) are included. The calculation has been done with a spectral binning of 60 eV over a range of 0.2–30 keV. We have ignored Doppler smearing of the lines, which, for an ADAF, is on the order of the thermal broadening and is relatively small at the radii of interest. Nevertheless, Doppler effects are within the range of resolving powers of some upcoming X-ray missions and merit more careful treatment.

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**Fig. 1.** Electron density $n_e$ and electron temperature $T_e$ vs. radius $r$ (in Schwarzschild units) for two models of Sgr A*. NW refers to a model with no wind ($m$ independent of $r$), and W refers to one with a wind ($m \propto r^{0.4}$).

**Fig. 2.** Top panel: model X-ray line spectra of V404 Cyg (in quiescence), Sgr A*, and the nucleus of M87 (the spectrum of M87 is shifted downward by 0.3 in the log for clarity). The models assume that the accretion occurs via an ADAF with no mass loss to a wind. The spectra are shown with energy bins of 60 eV and have been corrected for interstellar absorption with the values of $N_H$ quoted in the text. Bottom panel: corresponding models for the case when there is a moderately strong wind: $m \propto r^{0.4}$. 
The calculations proceed outward from the innermost zone at \( r = 10^5 \). In each zone, we use the local density and temperature to compute the thermal emission. We include photoionization by all radiation emitted at smaller radii (including the continuum emission from the region inside \( r = 10^3 \)). However, we find that photoionization affects the ionization state of the abundant ions by at most a few percent. This results from the relatively inefficient conversion of accretion energy to X-ray luminosity in an ADAF (<0.1% in the models presented here). It stands in contrast to the dominance of photoionization in the coronae of low-mass X-ray binaries, which convert ~20% of the accretion energy to X-rays and produce UV and X-ray line emission in a photoionized corona (Ramon 1993; Ko & Kallman 1994). We have not included photoabsorption, but we confirmed a posteriori that it is not important in reducing the X-ray flux.

4. RESULTS

Figure 2 shows model X-ray spectra of V404 Cyg, Sgr A*, and M87 for NW models (top panel) and W models (bottom panel); the spectra have been corrected for absorption using the estimated \( N_H \). The ordinate shows the photon count rate per 60 eV bin in units of cm\(^{-2}\) s\(^{-1}\). For the ACIS detector on the Chandra X-ray Observatory (CXO, formerly the Advanced X-Ray Astrophysics Facility), for example, with an effective area of ~300 cm\(^2\) and an integration time of \( 3 \times 10^4 \) s, the number of counts we may expect to detect in an observation is the photon count rate multiplied by ~\( 10^7 \) cm\(^2\) s\(^{-1}\). XMM, with an order of magnitude larger collecting area, can do much better. We see from Figure 2 that several of the lines in the model spectra could be observed with good signal-to-noise ratios with these experiments.

Table 1 lists equivalent widths of some lines. In general, we expect to see lines of H-like and He-like ions of high-Z elements. Figure 3 shows the equivalent widths of a few lines as a function of the outer radius for the Sgr A* model with a wind. The equivalent width of each line rises as the temperature declines to the characteristic temperature at which the line is formed. As the temperature falls still lower, there is little emission in either the line or the continuum at that energy, and the equivalent width remains constant. By studying the relative intensities of different lines, it would be possible to estimate how much gas is present at different temperatures; moreover, because of the near one-to-one mapping between temperature and radius at the radii \( r \sim 10^{-1} \) to \( 10^{-2} \) of interest (see Fig. 1), we could estimate the run of gas density with radius.

Both Figure 2 and Table 1 show a striking difference between nonwind (NW) and wind (W) models, with the latter producing significantly stronger lines. NW models are typically more Compton dominated than W models (Quataert & Narayan 1998), and, therefore, have less thermal emission. Also, because \( m \) is a rising function of \( r (m \propto r^{0.4}) \), W models have relatively more gas at larger radii (Fig. 2). Since the bulk of the line emission comes from radii outside about \( 10^5 \) (Fig. 3), this dramatically enhances the line emission in these models.

5. DISCUSSION

We have shown that high-resolution X-ray spectra of low-luminosity accreting black holes could reveal interesting emission lines if the accretion in these sources occurs via an ADAF. Some of the X-ray lines could be observed with good signal-to-noise ratios with CXO, XMM, and Astro-E, or the proposed Constellation-X. High-luminosity sources with ADAFs may be less interesting, since the lines could be swamped by Comptonized emission.

Detection of X-ray lines with any reasonable strength would imply an ADAF with a large outer radius and would rule out

### TABLE 1

| Line     | VNW | VW  | SNW | SW  | MNW | MW  |
|----------|-----|-----|-----|-----|-----|-----|
| O viii   | 0.0 | 0.0 | 0.0 | 0.6 | 0.6 | 0.6 |
| O viii   | 0.0 | 1.3 | 3.1 | 47.5| 0.2 | 47.2|
| Mg xi    | 0.0 | 0.1 | 0.3 | 5.6 | 0.0 | 5.4 |
| Mg xii   | 0.0 | 1.4 | 2.6 | 31.0| 0.2 | 30.6|
| Si xiii  | 0.0 | 0.8 | 2.4 | 37.4| 0.2 | 36.3|
| Si xiv   | 0.0 | 6.0 | 8.2 | 79.8| 0.6 | 79.1|
| S xvii   | 0.0 | 1.8 | 3.2 | 40.4| 0.2 | 39.4|
| Ar xviii | 0.1 | 7.2 | 6.7 | 50.1| 0.5 | 49.8|
| Ca xix   | 0.1 | 2.9 | 3.0 | 31.0| 0.2 | 30.3|
| Ca xix   | 0.1 | 7.1 | 4.8 | 28.4| 0.4 | 28.3|
| Fe xvi   | 0.0 | 1.7 | 1.1 | 10.1| 0.1 | 9.8 |
| Fe xvi   | 0.0 | 2.7 | 1.6 | 7.8 | 0.1 | 7.8 |
| Fe xvii  | 0.0 | 1.6 | 0.7 | 7.5 | 0.1 | 7.3 |
| Fe xvi   | 0.1 | 110 | 50.9| 327 | 3.6 | 315 |
| Si xiv   | 0.5 | 41.7| 19.5| 124 | 1.6 | 121 |
| Fe xvii  | 0.5 | 43.5| 19.3| 134 | 1.5 | 131 |
| Fe xvii  | 0.2 | 23.0| 10.2| 70.0| 0.7 | 67.1|
| Fe xvii  | 0.2 | 35.0| 15.5| 160 | 1.2 | 155 |
| Fe xvi   | 1.7 | 79.1| 60.5| 190 | 4.7 | 189 |
| Fe xvi   | 0.4 | 16.4| 13.7| 40.4| 1.1 | 40.6|
| Ni xxv   | 0.1 | 6.4 | 3.1 | 18.0| 0.2 | 17.3|
| Ni xxv   | 0.3 | 3.9 | 3.4 | 9.4 | 0.3 | 9.5 |

Note.—These lines are in ADAF models of V404 Cyg with no wind (VNW) and with wind (VW), Sgr A* with no wind (SNW) and with wind (SW), and M87 with no wind (MNW) and with wind (WN).
a Compton-dominated corona model. Models with winds have significantly larger equivalent widths than those without. If the strengths of many lines are measured, both the size of the ADAF and the presence or absence of a wind could be determined. Finally, although we have not computed it, high-resolution observations of line profiles have the potential to probe the dynamics of the thermal gas and thereby provide strong tests of models. Doppler effects could be resolved with the spectrometers on CXO, XMM, and Astro-E.

An important result is that the models predict photoionization to be unimportant. This is a unique feature of the ADAF model and distinguishes it from corona models. There are several X-ray diagnostics with which it should be possible to distinguish collisionally ionized hot plasma from photoionized gas; in the latter, X-ray lines are produced by recombination or by fluorescence rather than collisional excitation (Liedahl et al. 1992; Kallman 1995; Bautista et al. 1998). Because of the dominance of recombination, line ratios such as Fe xxvi/Fe xxv remain constant over a large range in radii in photoionized accretion disk coronae (ADCs), while the Fe xxvi/Fe xxv ratio varies with temperature, and hence with radius, in the ADAF models (Fig. 3). Another promising diagnostic for recombination is the ratio of the 1s–2s 1P resonance line to the 1s–2s 5S forbidden line in any of the He-like ions (e.g., the lines \( \lambda 1.850 \) and \( \lambda 1.867 \) of Fe xxv). While the ADC models were computed with high X-ray luminosities, the X-ray lines simply scale with the ionization parameter. The difference between ADAF and ADC models should be very robust, and it may be a way to distinguish black holes from neutron stars in low-luminosity X-ray sources.

The assumption of ionization equilibrium in the calculations is somewhat marginal, since the infall time is comparable to the ionization times of Fe xxv and Fe xxvi in the region of interest. The details depend on the viscosity parameter, but the overall result of the departure from ionization equilibrium will be to increase the intensities of the emission lines. The departure from equilibrium is in the opposite sense from that caused by photoionization, making it easier to distinguish from the photoionized case by way of emission-line diagnostics.

Other limitations of the present models also need to be noted. We do not include any emission from intermediate-temperature gas in the transition region between the outer disk and the ADAF and/or corona. In the wind models, we calculate only the line emission from the accretion flow and ignore radiation from the wind. Also, there could be line emission from diffuse hot gas surrounding the source (e.g., in Sgr A*; Koyama et al. 1996) that sometimes may be hard to distinguish from the accretion flow.

Of the models discussed here, those of V404 Cyg are perhaps the most secure. It is the only one of the three sources for which the X-ray luminosity is known accurately (Narayan et al. 1997) and for which we have a reliable estimate of \( m \). The size of the ADAF zone is also constrained by \( H \alpha \) line measurements. However, our model of the corona above the outer disk is somewhat crude.

The situation is worse for the other two sources. The X-ray emission from the accretion flow in Sgr A* is not well constrained, both because of the poor angular resolution of current observations, which cannot distinguish the black hole from the surrounding diffuse gas, and because of the large uncertainty in the absorbing column to the source. Both problems can be solved with future X-ray observations. If the X-ray continuum is not much below the estimate used by Narayan et al. (1998a), then Figure 2 indicates that line emission would be relatively easy to observe.

In the case of M87, it is not clear that the observed X-rays (Reynolds et al. 1996) necessarily come from the accretion flow onto the central black hole. The size of the ADAF too is highly uncertain; \( r_{\text{out}} \) could have any value from \( 10^3 \) to \( 10^5 \). Again, future observations will clarify the situation. In an optimistic scenario (the bottom panel of Fig. 2), lines should be seen readily.

The better than 1° angular resolution of the ACIS instrument on CXO will be particularly effective at eliminating any confusion from the surrounding gas in Sgr A* or from extraneous point sources in M87. For both sources, 1° corresponds to \( \sim 10^5 \) Schwarzschild radii, which is the assumed size of the ADAF.

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