THE QUIESCENT EMISSION SPECTRUM OF CENTAURUS X-4 AND OTHER X-RAY TRANSIENTS CONTAINING NEUTRON STARS

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ABSTRACT

We use the observed optical-UV and X-ray emission spectrum of Cen X-4 during quiescence to constrain models for the accretion flow in this system. We argue that the optical-UV emission is not due to an optically thick quiescent accretion disk, nor due to synchrotron emission from an advection-dominated accretion flow (ADAF). Emission from the bright spot could account for the observed optical-UV component if the mass transfer rate in Cen X-4 is \( \gtrsim 2 \times 10^{16} \) g s\(^{-1}\). Although the presence of an ADAF around the neutron star leads to Compton upscattering of the soft X-ray photons radiated from the stellar surface, we find that this process alone cannot account for the power-law component seen in the quiescent X-ray spectrum of Cen X-4 and other X-ray transients containing neutron stars; this result is independent of whether the source of soft photons is incandescent thermal emission or accretion-powered emission. We conclude that, in models which invoke the presence of an ADAF and a propeller effect for the quiescence of X-ray transients containing neutron stars, the intrinsic emission from the ADAF must contribute very little to the optical-UV and X-ray emission observed. If these ADAF + propeller models are correct, the X-ray power-law component observed must arise from regions where the gas impacts the neutron star surface. Variability studies could greatly help clarify the role of the various emission mechanisms involved.

Subject headings: accretion, accretion disks — binaries: close — stars: magnetic fields — stars: neutron — X-rays: stars

1. INTRODUCTION

Soft X-ray transients (SXTs) are close binary systems in which a low-mass secondary (either a main-sequence star or a subgiant) transfers mass via Roche-lobe overflow onto a black hole (BH) or neutron star (NS) primary (see reviews by Tanaka & Lewin 1995; van Paradijs & McClintock 1995; White, Nagase, & Parmar 1995). SXTs spend most of their lifetimes in a low-luminosity quiescent state, but occasionally undergo dramatic outbursts during which both the optical and X-ray emission increase by several orders of magnitude (e.g., Chen, Shrader, & Livio 1997; Kuulkers 1998). SXTs provide us with some of the best stellar-mass black hole candidates known to date, thanks to lower limits set on the mass of the accretor via the observation of Doppler-shifted lines in the spectrum of the secondary during quiescence (see, e.g., McClintock 1998).

While observations (see, e.g., Tanaka & Shibazaki 1996) indicate that SXTs accrete matter via a standard thin disk (Shakura & Sunyaev 1973) during outburst, the situation appears more complex in quiescence (see, e.g., Lasota 1996). Narayan, Barret, & McClintock (1997a; see also Narayan, McClintock, & Yi 1996) proposed that accretion in quiescent BH SXTs proceeds via a two-component accretion flow (ADAF; see Narayan, Mahadevan, & Quataert 1998b for a review of ADAFs) surrounded by an outer thin accretion disk. According to these models, the unusually low luminosities of BH SXTs in quiescence is due to the defining property of ADAFs: the bulk of the viscously dissipated energy is stored in the gas and advected with the flow into the black hole (Ichimaru 1977; Rees et al. 1982; Narayan & Yi 1994, 1995; Abramowicz et al. 1995; Narayan et al. 1996, 1997a). By contrast, in NS SXTs all the advected energy is expected to be radiated from the neutron star surface, resulting in a much higher radiative efficiency of the accretion flow even in the presence of an ADAF (Narayan & Yi 1995). This distinction between black hole and neutron star systems motivated a comparison of the outburst amplitudes of BH SXTs and NS SXTs as a function of their maximum luminosities by Narayan, Garcia, & McClintock (1997b) and Garcia et al. (1998). These authors showed that the observations reveal systematically lower relative luminosities in BH SXTs and argued that this constitutes a confirmation of the presence of an event horizon in BH SXTs.

Menou et al. (1999) developed ADAF + thin disk accretion models for quiescent BH and NS SXTs that account for the luminosity differences between the two classes of systems (see also Lasota 2000). However, the relatively low quiescent luminosities of NS SXTs can be reconciled with the model predictions only if an efficient “propeller effect” (Illarionov & Sunyaev 1975) operates during quiescence, so that the magnetosphere of the rapidly rotating neutron star prevents much of the accreting material from reaching the neutron star surface (see also Asai et al. 1998; Zhang, Yu, & Zhang 1998).

An alternative explanation for the quiescent X-ray emission of NS SXTs has been proposed by Brown, Bildsten, & Rutledge (1998). These authors argue that nuclear reactions in the crust of neutron stars, triggered during the outbursts of NS SXTs, efficiently heat up the NS cores in these

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systems. The energy deposited during an outburst is reemitted during quiescence at a rate sufficient to power the observed quiescent emission (see also Rutledge et al. 1999). Recently, Campana & Stella (2000) also proposed that the relativistic wind of the NS (in a pulsar regime) in quiescent SXTs could be responsible for part of the X-ray emission observed; the X-rays are produced by the impact of the wind on the gas stream flowing from the companion star.

So far, the quiescent emission of NS SXTs has been mainly discussed in terms of their luminosity, whereas it is likely that spectral information will help discriminate between the proposed emission mechanisms discussed above (see, e.g., Rutledge et al. 2000). In this paper, we construct models for the broadband emission spectrum of quiescent NS SXTs, with a particular emphasis on Cen X-4. Our main goal is to test the ADAF + propeller scenario proposed by Menou et al. (1999), but some of our results also have implications for the incandescence scenario put forward by Brown et al. (1998). An important motivation for this work is the recent finding by McClintock & Remillard (2000) that Cen X-4 (a NS SXT) and A0620-00 (a BH SXT), despite similar orbital periods, show significantly different quiescent optical-UV emission. This result could be an indication of the different nature of the accreting compact object in the two systems.

In § 2, we recall important observational properties of the NS SXT Cen X-4, which are later used to constrain our models. In § 3, we discuss several candidates for the quiescent optical-UV emission of Cen X-4. We then turn to models of the X-ray spectrum in § 4. Finally, we discuss consequences, limitations, and possible extensions of this work in § 5.

2. AVAILABLE CONSTRAINTS

2.1. Geometry and Masses

The orbital period of Cen X-4 is \( P_{\text{orb}} = 15.1 \) hr. The mass of the secondary is not known precisely but it is clearly small; we take \( M_2 = 0.15 \, M_{\odot} \) (White et al. 1995). For the mass of the neutron star, we adopt \( M_1 = 1.4 \, M_{\odot} \), corresponding to a binary mass ratio \( q = 0.1 \) (Charles 1998). The inclination of the system is \( i \approx 35^\circ - 40^\circ \) (Chevalier et al. 1989; McClintock & Remillard 1990).

With these parameters, we estimate an orbital separation \( a = 2.45 \times 10^{11} \) cm, a circularization radius \( R_{\text{circ}} = 7.5 \times 10^{10} \) cm, and a value \( R_{\text{L,1}} = 1.8 \times 10^{11} \) cm for the distance from the NS to the L1 Lagrange point (Frank, King, & Raine 1992). Throughout this paper, a distance estimate \( d = 1.2 \) kpc is used for Cen X-4 (Chevalier et al. 1989; Barret, McClintock, & Grindlay 1996).

According to van Paradijs & Verbunt (1984), the fluences of the two known outbursts of Cen X-4 are \( 3.2 \times 10^{44} \) ergs (July 1969) and \( 3 \times 10^{43} \) ergs (May 1979). Using the 1979 outburst fluence, the 10 yr of quiescence and a reasonable value for the radiative efficiency during outburst \( (\eta \equiv L/Mc^2 = 0.1) \) yields an average mass transfer rate \( M_T \approx 10^{15} \) g s\(^{-1}\) for the system. The 10 times larger fluence of the 1969 outburst could indicate a much larger average \( M_T \), but we do not use it here in the absence of a value for the period of quiescence preceding the outburst. Note that the mass transfer rate could also be larger if accretion proceeds via an ADAF at a significant rate during \( (\approx 10 \) yr) of quiescence but is not “seen” because an efficient propeller acts during this phase. The value \( 10^{15} \) g s\(^{-1}\) should therefore probably be considered as a lower limit to \( M_T \); in the following sections we consider values of \( M_T \leq 5 \times 10^{16} \) g s\(^{-1}\).

2.2. Emission Spectrum in Quiescence

An optical-UV spectrum of Cen X-4 has recently been reported by McClintock & Remillard (2000). During their observations, Cen X-4 was in quiescence with \( V \approx 18.2 \); however, on occasion the system is observed to be as faint as \( V \approx 18.6 \) (Chevalier et al. 1989). The emission is consistent with being roughly flat in \( \nu L_\nu \) (with an apparent peak around \( \log \nu (\text{Hz}) \approx 15.1) \); it extends up to \( \log \nu (\text{Hz}) \approx 15.2 \) (above which no data are available) for a total luminosity \( L_{\text{opt-UV}} \approx 0.8 \times 10^{32} \) ergs s\(^{-1}\). This is in clear contrast to the optical-UV spectrum of the BH SXT A0620-00 (of similar \( P_{\text{orb}} \), which shows a very strong cutoff at \( \log \nu (\text{Hz}) \approx 15.1 \) (McClintock & Remillard 2000). The spectra of both systems contain a strong and relatively broad emission line of Mg II 2800 Å.

Two-component, blackbody + power-law fits to the quiescent X-ray emission spectrum of Cen X-4 give a luminosity \( L_{\text{X}} \approx 2 \times 10^{32} \) ergs s\(^{-1}\) in the 0.5–10 keV band; \( \approx 55\% \) of the flux is in the blackbody (hereafter BB) component of temperature, \( T_{\text{BB}} \approx 0.15 \) keV, and the rest is in the power-law component with photon index \( \alpha_{\text{phot}} = 1.9 \pm 0.3 \) (Asai et al. 1996; see also Asai et al. 1998). Similar fits to the quiescent X-ray emission of the NS SXT Aql X-1 give a luminosity \( L_{\text{X}} \approx 6 \times 10^{32} \) ergs s\(^{-1}\) in the 0.5–10 keV band; \( \approx 60\% \) of the flux is in the BB component of temperature \( T_{\text{BB}} \approx 0.3 \) keV, and the rest is in the power-law component with photon index \( \alpha_{\text{phot}} = 1.0 \pm 0.3 \) (Campana et al. 1998).

Note that Rutledge et al. (1999) have argued, using fits to neutron star hydrogen atmosphere models, that the available X-ray spectral data for NS SXTs in quiescence are consistent with thermal emission from the entire surface of the neutron star. They find \( T_{\text{NS}} \approx 0.1 \) keV for Cen X-4 and \( T_{\text{NS}} \approx 0.1–0.2 \) keV for Aql X-1.

3. INTERPRETING THE OPTICAL-UV EMISSION

We consider three possible candidates for the quiescent optical-UV emission of Cen X-4 (and other NS SXTs): the emission from a quiescent disk as predicted by the disk instability model (DIM; see Cannizzo 1993 for a review), the emission from the bright spot, where the stream of gas from the companion star impacts the outer regions of the disk, and the ADAF synchrotron emission.

3.1. Contribution from the Quiescent Accretion Disk

In the ADAF + thin disk model of Narayan et al. (1997a) for quiescent BH SXTs (see also Lasota, Narayan, & Yi 1996), only the inner ADAF contributes to the observed optical and UV emission. In quiescence, the emission of the truncated disk is primarily in the infrared. A similar conclusion applies to NS SXTs if the transition radius between the inner ADAF and the outer thin disk is also large in these systems (for BH SXTs, a typical value in the models is \( R_{\text{u}} = 10^4 R_{\text{g}} \), where \( R_{\text{g}} = 3 \times 10^5 (M_1/M_{\odot}) \text{ cm} \) is the Schwarzschild radius). However, the location of this transition radius is very uncertain (e.g., Menou et al. 1999); the disk may extend much farther inward. In this case, could the disk account for or contribute significantly to the observed optical-UV emission in Cen X-4?
Note that the assumption of large optical thickness is justified for most of the disk. In the innermost regions, however, this assumption may not hold. A typical value of the surface density is

$$\Sigma \lesssim \Sigma_{\text{max}} \approx 12 \sigma_{\text{cold}}^{-0.33} (R/10^{10} \text{ cm})^{1.14} \text{ g cm}^{-2},$$

where $\sigma_{\text{cold}}$ is the viscosity parameter for the quiescent disk (see, e.g., Hameury et al. 1998). This surface density can be small enough at small $R$ that the disk is marginally optically thin in a Rosseland-mean sense.

The four curves in Figure 1 correspond to quiescent disk models for an inclination $i = 40^\circ$ from the line of sight and a disk’s outer radius of $10^{11}$ cm (see § 2.1). Given the DIM constraint on the mass accretion rate, each of the four models is fully specified by two parameters: the inner disk radius, $R_{\text{in}}$, and the mass transfer rate in the outer part of the disk, $M_{\text{out}}$. Model 1 has parameters $R_{\text{in}} = 10^8$ cm and $M_{\text{out}} = 5 \times 10^{16}$ g s$^{-1}$. The emission spectrum for this maximal disk is indicated by the long-dashed curve in Figure 1. In the inner region, the accretion rate in the disk is limited to $M(R) = M_{\text{crit}}(R)$ to guarantee its stability. Model 2 has parameters $R_{\text{in}} = 10^8$ cm and $M_{\text{out}} = 5 \times 10^{16}$ g s$^{-1}$. The emission spectrum of this disk model is indicated by the short-dashed curve in Figure 1. The disk truncation at $10^8$ cm corresponds to a reasonable magnetospheric radius in the case of disk accretion at a rate $M = M_{\text{crit}}(R)$ onto a neutron star of magnetic field strength $B = 10^8$ G. Model 3 has parameters $R_{\text{in}} = 10^8$ cm and $M_{\text{out}} = 10^{16}$ g s$^{-1}$. This model is similar to model 2, except for a reduced value of $M_{\text{out}}$, which is consistent with the estimated mass transfer rate in Cen X-4. Model 4 has parameters $R_{\text{in}} = 10^8$ cm and $M_{\text{out}} = 10^{16}$ g s$^{-1}$. In this model, indicated by the solid curve in Figure 1, the accretion rate in the disk is limited to $M(R) = 1/3 M_{\text{crit}}(R)$ in the inner regions. This is the model that is the closest to the predictions of a full, time-dependent disk instability calculation.

The models of quiescent disks shown in Figure 1 are luminous enough to account for the observed quiescent optical-UV emission of Cen X-4. However, the spectral discrepancy between the models and the data is gross. Even the maximal model is far too faint in the UV to account for that portion of the spectrum. This is a more detailed restatement of the argument made by Wheeler (1996), who noticed that the blackbody temperatures needed to fit the optical-UV spectra of quiescent BH SXTs are higher than the maximum values allowed by the DIM (since such a disk would experience an outburst immediately). The argument is stronger for Cen X-4 because the spectrum extends up to even higher frequencies in the UV. An optically thick disk spectrum that would approximately fit the optical-UV data in Figure 1 would have an effective temperature at its inner edge of $T_{\text{in}} \sim 20,000$ K, which would lead to an immediate outburst according to the DIM. Thus, assuming that the canonical disk blackbody spectrum is a reasonable approximation, we conclude that an optically thick disk cannot be responsible for the observed quiescent emission of Cen X-4.

3.2. Contribution from the Bright Spot

Optical and UV emission from the bright spot, where the stream of gas transferred by the companion impacts the disk, is seen in dwarf novae during quiescence; its contribution has been isolated in eclipsing dwarf novae (Warner 1995). Since dwarf novae are very similar to SXTs, except
for having a primary star that is a white dwarf, some or all of the quiescent optical-UV emission of Cen X-4 could be due to the bright spot.

We estimate the maximum luminosity of the bright spot as follows (see, e.g., Livio 1993). The gas is essentially free-falling from the L₁ point at the surface of the companion star to its impact point on the disk. Calculations by Lubow (1989) suggest that the minimum radius reached by such a stream before impact is ~1/2 the circularization radius for a low-q system such as Cen X-4. Taking the maximum luminosity of the bright spot to be

\[ L_{\text{BS}} = \frac{GM_1 M_2}{0.5 R_{\text{circ}} - R_{\text{L1}}}, \]

we find that the quiescent optical-UV flux of Cen X-4 can be powered by emission from the bright spot if the mass transfer rate is \( M_T \approx 2 \times 10^{16} \text{ g s}^{-1} (d/1.2 \text{ kpc})^2 \). Since this is not incompatible with the estimates for \( M_T \) discussed in § 2.1, it seems a plausible explanation for the observed emission. If the stream impacts the disk at the outer edge, a mass transfer rate a factor of a few times larger would be required. This possibility, which is preferred over the two other emission mechanisms considered here (§ 3.1 and § 3.3), could presumably be tested by studying the variability of the quiescent optical-UV component of Cen X-4.

We note, however, that the blackbody temperature required to fit the quiescent optical-UV spectrum of Cen X-4 is \( T_{\text{BB}} \approx 26,000 \text{ K} \). This is significantly higher than the values \( T_{\text{BB}} \approx 11,000-16,000 \text{ K} \) usually inferred for dwarf novae (Warner 1995). Similarly, the difference between the quiescent optical-UV spectrum of Cen X-4 and A0620-00 (which would require only \( T_{\text{BB}} \approx 13,000 \text{ K} \) remains without a clear explanation if the bright-spot hypothesis is adopted.

3.3. Contribution from the ADAF Synchrotron Emission

The optical-UV emission from the accretion flow has been attributed to the ADAF synchrotron emission in the models for quiescent BH SXTs of Narayan et al. (1997a). According to the models of Menou et al. (1999), an ADAF is present in the inner regions of the accretion flow of Cen X-4 during quiescence, and mass is mainly flung away at the magnetosphere by an efficient propeller effect. Some optical-UV emission is expected from the ADAF (it does not possess strong winds that suppress synchrotron emission; Quataert & Narayan 1999). Interestingly, the synchrotron self-absorption cutoff is expected at higher frequencies for quiescent NS SXTs than for quiescent BH SXTs because of the smaller mass of \( M_1 \) of the primary (Mahadevan 1997). The presence of a magnetosphere, however, complicates the picture, at least by truncating the innermost, hottest and brightest regions of the synchrotron-emitting accretion flow.

Here, we model the ADAF emission in the simplest way, as it has been done so far for quiescent BH SXTs (see Narayan et al. 1997a, 1998a). We adopt the following model parameters: \( \alpha_{\text{ADAF}} = 0.1 \) (viscosity parameter), \( \delta = 0.01 \) (direct electron viscous heating), \( \beta = 10 \) (ratio of gas to magnetic pressure), \( p = 0 \) (no wind), and \( i = 40° \) (inclination). The ADAF is assumed to extend from \( R_{\text{out}} = 10^{4}R_{\text{S}} \approx 3 \times 10^{9} \text{ cm} \) down to \( R_{\text{in}} = 10R_{\text{S}} \) (a reasonable value for the magnetospheric radius in the case of accretion via an ADAF onto a neutron star of magnetic field strength \( B = 10^8 \text{ G} \), for the typical accretion rates considered here; see Menou et al. 1999). Since most of the synchrotron emission comes from the innermost regions of the ADAF, the details of how the ADAF solution matches the thin disk are unimportant as long as the transition radius is large. We neglect here possible complications due to the “boundary layer” at the magnetosphere, and processes inside the magnetosphere. The soft X-ray emission originating from the vicinity of the NS (as observationally inferred for Cen X-4 and other NS SXTs) would only slightly affect the predicted ADAF emission spectrum in the optical-UV (as shown by calculations in § 4), so we neglect it here because it does not modify our conclusion below.

Figure 2 shows predictions for the ADAF synchrotron emission at three accretion rates: \( \dot{m}_{\text{ADAF}} = 2 \times 10^{-3} \) (dashed line), \( 10^{-3} \) (solid line) and \( 5.5 \times 10^{-4} \) (dotted line), in units of the Eddington accretion rate [taken here as \( M_{\text{edd}} = 1.39 \times 10^{18}(M_1/M_\odot) \text{ g s}^{-1} \)]; the corresponding physical accretion rates are approximately \( 4 \times 10^{15}, 2 \times 10^{15}, \) and \( 10^{15} \text{ g s}^{-1}, \) respectively. None of the models provides an acceptable description of the data. The predicted ADAF synchrotron spectra that are bright enough to account for the quiescent optical-UV emission are spectrally discrepant, in the sense that the predicted peak synchrotron frequency is systematically at a much lower frequency than that at which the observed spectrum peaks (\( \log [\nu(\text{Hz})] \approx 15.1 \)).

We have checked, by exploring the ADAF parameter space, that this result is robust to changes in the various model parameters. The predicted synchrotron peak frequency is not significantly affected by variations of \( \alpha_{\text{ADAF}} \) or \( \delta \) (see Narayan et al. 1997a for an exploration of the param-
eter space of ADAFs). It is affected by changes in the parameters $R_n$, $\beta$, and $p$, but it turns out that no model can reproduce at the same time the observed luminosity and location of the synchrotron peak. The effect of varying $R_n$ is illustrated by the dashed-dotted line in Figure 2, which corresponds to a model with $\dot{m}_{\text{ADAF}} = 10^{-3}$ (as for the solid line) but with $R_n = 20R_s$. The synchrotron emission is substantially reduced by the slight increase of $R_n$. A model with $R_n = 3R_s$ (i.e., without magnetospheric truncation of the ADAF), which predicts a larger peak synchrotron frequency as desired, is ruled out on other grounds, however. Indeed, without magnetospheric interaction, no propeller effect is expected, so that the release from the entire NS surface of all the accretion energy contained in the hot gas both overpredicts by orders of magnitude the observed quiescent bolometric luminosity of Cen X-4 and dramatically cools the ADAF (strongly reducing its synchrotron emission), as discussed by Yi et al. (1996).

Reducing the value of $\beta$ (i.e., increasing the magnetic pressure in the ADAF) leads to larger values of the synchrotron peak frequency, as shown by Narayan et al. (1997a). Pushing the value of $\beta$ to unity (corresponding to an extreme equipartition case) still does not bring the synchrotron peak to the desired location (see Narayan et al. 1997a for the effect of changing $\beta$). The only model that can account for the large value of the synchrotron peak frequency is a model with a necessarily large $\dot{m}$ (even if $\beta = 1$); such a model always largely overpredicts the observed optical-UV emission of Cen X-4 in quiescence (see Figure 2 for examples). Even allowing for the possibility of winds emanating from the ADAF (i.e., models with $p > 0$) does not solve the problem because winds reduce both the overall synchrotron emission and the value of the synchrotron peak frequency at the same time (see Quataert & Narayan 1999). Therefore, we conclude that ADAF models (which we tested over a wide range of parameter space) cannot reproduce the level of optical-UV emission seen from Cen X-4 in quiescence and the location of the peak frequency observed. If there is an ADAF present in the inner regions of the accretion flow, its emission must be weak enough that it is swamped by the emission component that produces the observed optical-UV emission. The ADAF emission can easily be reduced to low levels if $\dot{m}$ is low enough and/or the magnetospheric truncation of the ADAF occurs at large enough radii.

4. INTERPRETING THE X-RAY EMISSION

We now consider the quiescent X-ray emission of Cen X-4. Unlike the optical-UV emission, we can be quite confident that the X-ray emission comes from regions near the NS (since coronal emission by the companion star has been ruled out for quiescent SXTs; Bildsten & Rutledge 2000). There are two competing models for the origin of the X-ray emission from the neutron star surface: (1) the accretion luminosity that is powered by the thermal and bulk kinetic energy of the gas impacting the surface, and (2) the incandescent luminosity due purely to thermal emission from the intrinsically hot NS (Brown et al. 1998).

The observed power-law component (§2.2) cannot be due to incandescent emission, which implies that an accretion flow is responsible for at least part of the X-ray emission observed. In the ADAF + propeller scenario, a natural origin for this component could be the ADAF itself (although we argued in §3.3 that it cannot be the origin of the observed quiescent optical-UV emission in Cen X-4). Compton upscattering of the soft X-ray photons by the hot electrons in the ADAF would produce a hard X-ray component that could be interpreted as a power-law component in a restricted energy band.

In order to test this hypothesis, we use a modified version of the ADAF spectral model, developed by R. Narayan, which includes the possibility of radiation emanating from the NS surface in the spectral calculations. Apart from this extra feature, the radiative transfer treatment is identical to that described in Narayan et al. (1997a). Models are characterized by two extra parameters: $f_{\text{acc}}$ is the fraction of the mass accreted through the ADAF that reaches the NS surface ($<1$ if a propeller effect is acting in quiescence), and $f_{\text{surf}}$ is the fraction of the NS surface from which the accretion energy of the gas reaching the NS surface is radiated to infinity (i.e., $f_{\text{surf}}$ essentially characterizes the geometry of the magnetically channeled accretion onto the NS; the polar cap axis is assumed to be the same as the axis perpendicular to the accretion plane). In this section, we only consider the case of blackbody-type emission from the NS surface (i.e., we assume that the energy carried in by the gas has been thermalized before being radiated away). Given the values of $\dot{m}_{\text{ADAF}}$, $f_{\text{acc}}$, and $f_{\text{surf}}$, the temperature $T_{\text{BB}}$ of the blackbody emission and the emitted spectrum are easily computed for an assumed NS radius of 10 km. This emission is assumed to be radiated isotropically from the NS surface in the Comptonization calculations (see Narayan et al. 1997a for other details on the radiative transfer treatment).

Figure 3 shows a representative spectrum at infinity for a model in which an ADAF surrounds an NS that emits blackbody-type radiation from its surface (solid line). In this specific example, the blackbody emission (dotted line) emanates from the entire NS surface (i.e., $f_{\text{surf}} = 1$), with a temperature $T_{\text{BB}} = 0.1$ keV. This model represents, at the level of precision we are interested in here, the emission expected if an incandescent NS, as proposed by Brown et al. (1998; see Zavlin, Pavlov, & Shibanov 1996 and Rajagopal & Romani 1996 for atmosphere models), were surrounded by an ADAF. There is a clear Compton bump, centered at log $[\nu(\text{Hz})] = 18.5$, which is due to the Compton upscattering of the soft X-ray photons of the BB component in the ADAF. The same ADAF model without the BB component (Fig. 3, dashed line) shows slightly enhanced synchrotron emission because the cooling of the gas in the ADAF by Compton upscattering of the soft X-ray photons is absent in this case.

The Compton bump would be interpreted as a power-law component with $\lambda_{\text{phot}} \approx 1.5$ if it were observed only around log $[\nu(\text{Hz})] \sim 18$. An exploration of the parameter space of the models (i.e., variations of $T_{\text{BB}}$ and $f_{\text{surf}}$) shows that exclusively soft “power-law components,” with $\lambda_{\text{phot}} > 1.5$, are produced in models with total X-ray luminosities comparable to that observed from Cen X-4 in quiescence ($10^{32}$–$10^{33}$ ergs s$^{-1}$ in the 0.5–10 keV band). Perhaps more importantly, the fraction of the flux in the Compton component is invariably small compared to that in the BB component for this type of model (i.e., $\lesssim 5\%$–$10\%$ bolometric and $\sim$ a few

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2 Note the different definitions of $\beta$ adopted here and in Narayan et al. (1997a). For a given value of $\beta_p$ in Narayan et al. (1997a), the corresponding value of $\beta$ as defined in the present paper is $\beta = \beta_p/(1 - \beta_p)$. 

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This conclusion is independent of the origin of the BB component (incandescent thermal emission or accretion-powered emission).

5. DISCUSSION AND CONCLUSION

We constructed models of the accretion flow in the NS SXT Cen X-4 during quiescence. Many of our conclusions can in principle be generalized to other NS SXTs. We do not find a satisfying explanation for the observed optical-UV and X-ray emission spectrum of Cen X-4 within the framework of ADAF + propeller accretion models.

We argued that the bright spot can power the quiescent optical-UV emission of Cen X-4 if the mass transfer rate of the system is \( \gtrsim 2 \times 10^{16} \) g s\(^{-1} \). This is larger than the estimates based on outburst fluences and therefore suggests, if correct, that a fair amount of "invisible" accretion occurs in quiescence, which could be due to an efficient propeller acting during this phase. Note that we did not consider the possibility of reprocessing of X-rays by the accretion disk for powering the optical-UV flux because the X-ray luminosity, \( L_X \approx 2 \times 3 \times 10^{32} \) erg s\(^{-1} \), appears insufficient to explain the strong optical-UV component, with \( L_{\text{opt-UV}} \approx 0.8 \times 10^{32} \) ergs s\(^{-1} \).

When ruling out emission from a quiescent disk, we neglected possible deviations from blackbody emission in the innermost regions of the disk. Most of the observed emission actually originates from the outer regions \( (R^2 \sigma T_\text{eff} \propto M_{\text{in}} / R \propto R^{1.5}) \), see eqs. [1] and [2], which are optically thick according to the disk instability model (DIM). For this reason, we do not expect possible complications for the emission in the inner regions of the disk to be sufficient to explain the spectral discrepancy shown in Figure 1. Conceivably, the presence of a disk chromosphere could induce spectral deviations from blackbody-type emission, but more detailed modeling is required to address this question. Note that the broad Mg II line in the spectrum of Cen X-4, with an integrated energy \( L_{\text{MgII}} \approx 2.8 \times 10^{30} \) erg s\(^{-1} \) (McClintock & Remillard 2000), does suggest emission from an optically thin disk chromosphere. The single-peaked shape can be explained by the superposition of two double-peaked doublet components separated by 7.2 Å, thereby supporting a disk origin for this line.

We argued that Compton upscattering of soft X-ray photons emitted at the surface of an NS by an ADAF is not sufficient to explain the power-law component inferred in the quiescent X-ray spectrum of Cen X-4 and other NS SXTs. Instead, most of the flux in the power-law component could be associated with the accretion-powered emission in higher density regions close to the NS surface (see, e.g., Shapiro & Salpeter 1975; Turolla et al. 1994; Popham & Sunyaev 2001; Medvedev & Narayan 2001; we note, however, that none of these models can be directly applied to the ADAF + propeller scenario because of discrepancies in the accretion rate or the geometry assumed).

Compton upscattering by a surrounding ADAF could also have applied to the scenario of Brown et al. (1998) if, for instance, the propeller effect were efficient enough in quiescence to prevent all the mass accreted via the ADAF from reaching the NS surface, so that the accretion-powered luminosity became negligible compared to the NS incandescent emission. However, the difficulties with this scenario are similar to the case of accretion-powered emission: Compton upscattering in the low-density ADAF is insufficient to produce the observed X-ray power-law emission.

Figure 3.—Amplitude of Comptonization by the hot electrons in an ADAF surrounding a neutron star (NS). In this specific example, the source of soft X-ray photons is blackbody (BB) emission from the entire NS surface with a temperature \( T_{\text{BB}} = 0.1 \) keV (dotted line). The dashed line corresponds to the original ADAF spectrum, in the absence of the BB component (model parameters are \( T_{\text{ADAF}} = 5 \times 10^{-4}, \delta_{\text{ADAF}} = 0.1, \beta = 10, \delta = 0.01, p = 0, \) and the ADAF extends from \( 10R_s \approx 3 \times 10^5 \) cm to \( 10^6 R_s \). The Compton bump that appears when the BB component is included (solid line) would be interpreted as a power-law component with photon index \( \alpha_{\text{phot}} \approx 1.5 \) in the 0.5–10 keV energy range. The total energy in the Compton bump is only a small fraction of that in the BB component because of the Compton \( \gamma \)-parameter \( \ll 1 \) in the ADAF.
Therefore, the origin of the power-law component in the incandescence scenario remains unclear.

Variability studies could therefore play an important role in clarifying which mechanisms operate in quiescent NS SXTs. For instance, variability in the BB component would rule out the scenario of Brown et al. (1998). Similarly, if coherent X-ray pulsations were to be observed in a quiescent NS SXT, they would occur in both the BB and the power-law component, according to the scenario presented in § 5, while they would not occur for the BB component according to the scenario of Brown et al. (1998). Campana & Stella (2000) have discussed additional variability characteristics expected in their pulsar scenario.

It is somewhat embarrassing that no obvious signature of accretion via an ADAF exists in the model proposed for the quiescent emission spectrum of Cen X-4. The ADAF remains unseen in optical-UV, perhaps because of the truncation by the magnetosphere; similarly, its X-ray emission must be dominated by accretion-powered emission at the surface of the NS, which has a much higher radiative efficiency than the ADAF. Consequently, studying the effect of possible winds from the ADAF (which would only reduce the intrinsic ADAF emission; Blandford & Begelman 1999; Quataert & Narayan 1999) is essentially irrelevant in the present context. This also means that it is impossible, if there is indeed an ADAF and a propeller acting in Cen X-4 during quiescence, to constrain the efficiency of the propeller relative to that of the winds at removing mass from the accretion flow.

Finally, we note that our study does not offer a clear explanation for the qualitative spectral difference between A0620-00 and Cen X-4 in the optical-UV. Although the presence of a magnetosphere in the case of Cen X-4 is expected to reduce the synchrotron ADAF emission relative to A0620, and therefore lead to spectral differences, this does not explain the significantly hotter UV emission of Cen X-4.

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REFERENCES

Abramowicz, M., Chen, X.-M., Kato, S., Lasota, J.-P., & Regge, O. 1995, ApJ, 438, L37
Asai, K., et al. 1996, PASJ, 48, 257
———. 1998, PASJ, 50, 611
Barret, D., McClintock, J. E., & Grindlay, J. E. 1996, ApJ, 473, 963
Bildsten, L., & Rutledge, R. E. 2000, ApJ, 541, 908
Blandford, R. D., & Begelman, M. C. 1999, MNras, 303, 1L
Brown, E. F., Bildsten, L., & Rutledge, R. E. 1998, ApJ, 504, L95
Campana, S., et al. 1998, ApJ, 499, L65
Campana, S., & Stella, L. 2000, ApJ, 541, 849
Cannizzo, J. K. 1993, in Accretion Disks in Compact Stellar Systems, ed. J. C. Wheeler (Singapore: World Scientific), 6
Charles, P. 1998, in Theory of Black Hole Accretion Disks, ed. M. A. Abramowicz, G. Bjornsson, & J. E. Pringle (Cambridge: Cambridge Univ. Press), 1
Chen, W., Shrader, C. R., & Livio, M. 1997, ApJ, 491, 312
Chevalier, C., Hovenkamp, S. A., Van Paradijs, J., Pedersen, H., & Van der Klis, M. 1999, A&A, 210, 114
Frank, J., King, A., & Raine, D. 1992, Accretion Power in Astrophysics (Cambridge: Cambridge Univ. Press)
Garcia, M. R., McClintock, J. E., Narayan, R., & Callanan, J. 1998, in Proc. 13th North American Workshop on Cataclysmic Variables, ed. S. Howell, E. Kuulkers, & C. Woodward (San Francisco: ASP), 506
Hameury, J.-M., Menou, K., Dubus, G., Lasota, J.-P., & Hurt, J.-M. 1998, MNras, 298, 1048
Ichimaru, S. 1977, ApJ, 214, 840
Idan, I., Lasota, J.-P., Hameury, J.-M., & Shaviv, G. 1999, Phys. Rep., 311, 213
Illarionov, A. F., & Sunyaev, R. A. 1975, A&A, 39, 185
Kuulkers, E. 1998, NewA Rev., 42, 1
Lasota, J.-P. 1996, in IAU Symp. 165, Compact Stars in Binaries, ed. J. van Paradijs, E. P. J. van den Heuvel, & E. Kuulkers (Dordrecht: Kluwer), 58
———. 2000, ApJ, 504, L95
Livio, M. 1993, in Accretion Disks in Compact Stellar systems, ed. J. C. Wheeler (Singapore: World Scientific), 243
Lubow, S. H. 1989, ApJ, 340, 1064
Mahadevan, R. 1997, ApJ, 477, 585
McClintock, J. E. 1998, in Accretion Processes in Astrophysics—Some Like it Hot, ed. S. Holt, & T. Kallman (Woodbury: AIP), 290
McClintock, J. E., & Remillard, R. A. 1990, ApJ, 350, 386
———. 2000, ApJ, 531, 956
Medvedev, M., & Narayan, R. 2001, ApJ, 554, 1255
Menou, K., Esin, A. A., Narayan, R., Garcia, M. R., Lasota, J.-P., & McClintock, J. E. 1999, ApJ, 520, 276
Narayan, R., Barret, D., & McClintock, J. E. 1997a, ApJ, 482, 448
Narayan, R., Garcia, M. R., & McClintock, J. E. 1997b, ApJ, 478, L79
Narayan, R., Mahadevan, R., Grindlay, J. E., Popham, R. G., & Gammie, C. F. 1998a, ApJ, 492, 554
Narayan, R., Mahadevan, R., & Quataert, E. 1998b, in The Theory of Black Hole Accretion Disks, ed. M. A. Abramowicz, G. Bjornsson, & J. E. Pringle (Cambridge: Cambridge Univ. Press), 48
Narayan, R., McClintock, J. E., & Yi, I. 1996, ApJ, 457, 821
Narayan, R., & Yi, I. 1994, ApJ, 428, L13
———. 1995, ApJ, 452, 710
Popham, R., & Sunyaev, R. 2001, ApJ, 547, 355
Quataert, E., & Narayan, R. 1999, ApJ, 520, 298
Rajagopal, M., & Romani, R. W. 1996, ApJ, 461, 327
Rees, M. J., Phinney, E. S., Begelman, M. C., & Blandford, R. D. 1982, Nature, 295, 17
Rutledge, R. E., Bildsten, L., Brown, E. F., Pavlov, G. G., & Zavlin, V. E. 1995, ApJ, 454, 945
———. 2000, ApJ, 529, 985
Rybicki, G. B., & Lightman, A. P. 1979, Radiative Processes in Astrophysics (New York: Wiley-Interscience)
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Shapiro, S. L., & Salpeter, E. E. 1975, ApJ, 198, 671
Tanaka, Y., & Lewin, W. H. G. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 126
Tanaka, Y., & Shibazaki, N. 1996, A&A&A, 34, 607
Turolla, R., Zampieri, L., Colpi, M., & Treves, A. 1994, ApJ, 426, L35
van Paradijs, J., & McClintock, J. E. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 58
van Paradijs, J., & Verbunt, F. 1984, in AIP Conf. Proc. 115, High Energy Transients in Astrophysics, ed. S. E. Woosley (New York: AIP), 49
Warner, B. 1995, Cataclysmic Variable Stars, (Cambridge: Cambridge Univ. Press)
Wheeler, J. C. 1996, in Relativistic Astrophysics: A Conference in Honor of Igor Novikov’s 60th Birthday, ed. B. Jones, & D. Markovic (Cambridge: Cambridge Univ. Press)
White, N. E., Nagase, F., & Parmar, A. N. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 1
Yi, I., Narayan, R., Barret, D., & McClintock, J. E. 1996, A&A&A, 120, 187
Zavlin, V. E., Pavlov, G. G., & Shibakov, Y. A. 1996, A&A&A, 315, 141
Zhang, S. N., Yu, W., & Zhang, W. 1998, ApJ, 494, L71