The Flared Disc Project: RXTE and ASCA observations of X 1822−371

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ABSTRACT
We present archival Rossi X-ray Timing Explorer (RXTE) and simultaneous Advanced Satellite for Cosmology and Astrophysics (ASCA) data of the eclipsing low mass X-ray binary (LMXB) X 1822−371. Our spectral analysis shows that a variety of simple models can fit the spectra relatively well. Of these models, we explore two in detail through phase resolved fits. These two models represent the case of a very optically thick and a very optically thin corona. While systematic residuals remain at high energies, the overall spectral shape is well-approximated. The same two basic models are fit to the X-ray light curve, which shows sinusoidal modulations interpreted as absorption by an opaque disc rim of varying height. The geometry we infer from these fits is consistent with previous studies: the disc rim reaches out to the tidal truncation radius, while the radius of the corona (approximated as spherical) is very close to the circularization radius. Timing analysis of the RXTE data shows a time lag from hard to soft consistent with the coronal size inferred from the fits. Neither the spectra nor the light curve fits allow us to rule out either model, leaving a key ingredient of the X 1822−371 puzzle unsolved. Furthermore, while previous studies were consistent with the central object being a 1.4 M⊙ neutron star, which has been adopted as the best guess scenario for this system, our light curve fits show that a white dwarf or black hole primary can work just as well. Based on previously published estimates of the orbital evolution of X 1822−371, however, we suggest that this system contains either a neutron star or a low mass (< ∼ 2.5 M⊙) black hole and is in a transitional state of duration shortward of 10^7 years.

Key words: accretion — neutron star physics — Stars: binaries — X-rays:Stars

1 INTRODUCTION

X 1822−371 is a low mass X-ray binary and is the prototypical ‘Accretion Disc Corona’ (ADC) source (White & Holt 1982). The 5.57 hr orbital period of X 1822−371 (White et al. 1981) exhibits a quasi-sinusoidal variation in both the X-ray and optical (see also Mason & Córdova 1982; Hellier & Mason 1989). In addition, there is an approximately 20 min long dip associated with partial obscuration of the X-ray source by the secondary mass-donating star (presumed to be filling its Roche lobe; see White et al. 1981, White & Holt 1982, Mason & Córdova 1982, Hellier & Mason 1989, and Hellier et al. 1992). Thus X 1822−371 is believed to be a near edge on source; however, since the X-ray dip—henceforth defined to be at zero orbital phase— is only partial, the X-rays are presumed to emanate from a very extended corona with a radius of the order of 3 × 10^{10} cm.

Assuming a distance of 2 kpc (Mason & Córdova 1982a), the observed X-ray flux corresponds to an isotropic luminosity of L_{iso} ~ 10^{36} ergs s⁻¹. The central X-ray source is obscured, however, and we only observe X-rays scattered into our line of sight. The intrinsic X-ray luminosity is therefore undoubtedly greater, perhaps substantially so (see §5). The properties and origin of this scattering corona are largely unknown. White & Holt (1982) postulated a corona, possibly optically thick, driven by a photoionizing radiation flux near the Eddington luminosity. In their model, a near Eddington luminosity is required to achieve the large scale height of the corona. Frank et al. (1987) postulated that the corona was due to interaction of the incoming accretion stream with the disc at the circularization radius. Viscous dissipation at radii within the circularization radius would in part lead to the vertical extent of the corona.

The sinusoidal modulation is associated with obscuration by material with a vertical extent of order 10^{10} cm (White & Holt 1982; Hellier & Mason 1989). Frank et al. (1987) postulated that this obscuring material is also located at the disc circularization radius. However, the fact that the optical light curve also shows a sinusoidal modulation and a dip with approximately twice the duration of that
in the X-ray suggests that this obscuring rim is actually at twice this radius, i.e., closer to the disc tidal truncation radius (Hellier & Mason 1989; see also §3 below). Again, this rim is associated with the interaction of the accretion stream with the accretion disc (Armitage & Livio 1996; Armitage & Livio 1998).

Perhaps the most confusing aspect of X 1822–371 has been its spectra. White et al. (1981) fit Einstein spectra with a flat, exponentially cutoff power law (photon index, $\Gamma \sim -1$, cutoff energy $\approx 17$ keV). Furthermore, they required a broad (4 keV wide) Fe line component with equivalent width $\sim 1$ keV and a soft excess that they attributed to either a 0.25 keV blackbody or possibly an Fe L complex. Hellier & Mason (1989), on the other hand, fit EXOSAT spectra with a flat power law ($\Gamma \approx -0.8$), an $\approx 2$ keV blackbody, and an Fe K$_\alpha$ line with 270 eV equivalent width. The flux of the blackbody had an implied emitting area consistent with 1/400 of the surface area of a neutron star. Hellier & Mason (1989) therefore postulated that this emission is indeed from a neutron star surface and is scattered into our line of sight by a very optically thin corona.

Several years later, Hellier et al. (1992) considered Ginga spectra of X 1822–371, and they attempted to fit the same model as for the EXOSAT data. Although such a model was the best simple fit that they could achieve, the fits were not adequate and yielded a reduced $\chi^2 \sim 10$. Furthermore, Hellier et al. noted that the dip at zero orbital phase was fractionally larger at higher energies. They interpreted this fact as indicating that the corona was in fact optically thick. Hellier et al. (1990) claim that over the orbit ($\approx 8$ keV and $\approx 7$ keV). Also required in these fits are a blackbody with $kT_{\alpha} \approx 23$, $kT_{\beta} \approx 7$ keV. Also required in these fits are a blackbody with $kT_{\alpha} \approx 1.8$ keV and an Fe K$_\alpha$ line with equivalent width 65–150 eV. This latter feature possibly could be in reality two lines (Fe K$_\alpha$/β), not adequately resolved from one another. P00 found no evidence for either an Fe K-edge or O K-edge; however, they claim a detection of a 1.3–1.4 keV edge with $\tau \approx 0.1–0.3$ that they associate with K-edges of Ne X and neutral Mg, or the L-edges of moderately ionized Fe. (See our discussion of §5, however.)

The question of whether X 1822–371 contains a neutron star, black hole, or even a white dwarf primary also is yet unresolved. The lightcurves have been fitted with a model with a 1.4 M$_\odot$ primary (Hellier & Mason 1989); however, as we discuss in §3 these fits do not uniquely determine the primary mass. To date, no variability has been detected that would uniquely point to a neutron star primary (see Hellier et al. 1990 for variability analysis of the Ginga data). Previous analyses only detected variability on the orbital time scales.

Facing a new generation of X-ray satellites, we decided to revisit X 1822–371 with the help of predominantly unpublished simultaneous archival Rossi X-ray Timing Explorer (RXTE) and ASCA data. Our goal is to assess the evidence gathered so far and to point out what we believe to be future avenues for cutting edge X-ray spectroscopy, as will be provided by the X-ray Multiple Mirror-Newton telescope (XMM-Newton) and Chandra. First, we discuss the orbital ephemeris (§2.1) and the gross spectral variations over the orbit (§2.2). We then consider two separate spectral models which can be considered as broadly representing an ‘optically thick corona’ and an ‘optically thin corona’ (§2.2). Using the RXTE lightcurves, we consider fits in multiple energy bands (§3). Here we consider both optically thick and optically thin coronae, and furthermore we consider white dwarf, neutron star, and low mass black hole primaries. The high frequency (10$^{-3}$–0.3 Hz) variability of the RXTE data is then considered (§4). We then discuss the implications of these analyses (§5) and present our conclusions (§6).

### Table 1. Observation Log.

| Satellite | Instr. | OBS ID | Start Date | Exp. Time |
|-----------|--------|--------|------------|-----------|
| RXTE      | PCA    | 10115-01 | 26 Sep. 96 | 21.6 ksec |
| ASCA      | SIS,GIS| 44015000 | 26 Sep. 96 | 28.5 ksec |
| ASCA      | SIS,GIS| 40019000 | 7 Oct. 93  | 38.5 ksec |

### 2 DATA ANALYSIS

In this paper we analyze a set of simultaneous RXTE and ASCA observations of X 1822–371 taken in 1996 and a separate set of ASCA observations from 1993, as summarized in Table 1. Details of the data reduction procedure are summarized in the Appendix. For RXTE we only consider data from the Proportional Counter Array (PCA), while for ASCA we consider data from both the Solid State Imaging Spectrometers (SIS) and the Gas Imaging Spectrometers (GIS).

We use the simultaneous RXTE/ASCA data to perform ‘global’, broad-band fits, and not for detailed line spectroscopy. In what follows, we therefore have combined the two separate SIS spectra into one spectrum and likewise we have combined the two separate GIS spectra into a single spectrum. As we use the 1993 ASCA spectra for detailed line modelling, we do not combine the separate SIS spectra for those observations.

#### 2.1 Orbital Evolution

Updated parameters on ephemeris and period changes have most recently been provided by P00, including all three data sets analyzed in this paper. To confirm the measurements by P00, we fitted the eclipse with a linear function attenuated by a Gaussian. Our fits agree with those of P00 to within the error bars (indicated by parentheses below). P00 et al. give a quadratic ephemeris for the eclipse midpoint as a function of orbital number, $N$, of

$$T_{\text{eci}} = 2445615.30964(15) + 0.232108785(50)N + 2.06(23) \times 10^{-11}N^2$$

(1)

This implies a period derivative of

$$\frac{dP}{dt} = 1.78(20) \times 10^{-10}$$

(2)

(See also Hellier et al. 1990.) Thus $\dot{P}^{-1} \approx 3.6 \times 10^6$ years.
We can now use this value to estimate the mass transfer rate in the system. We assume that a fraction $1 - f$ of the mass lost from the secondary is transferred to the primary, while the remaining fraction $f$ is lost from the system at the location of the primary (e.g., in the form of a central disc wind or jet); $M_2 = -(1 - f) M_1$. The angular momentum loss is then $J / f = f M_2 / M_2 q^2 / (1 + q)$. If we define the usual mass ratio $q \equiv M_2 / M_1$, where $M_1$ and $M_2$ are the masses of the primary and the secondary respectively, we can write the mass accretion rate onto the primary as

$$M_1 = M_1 \frac{q}{3(1 - q)} \frac{\dot{P}}{L} (1 - f) \left[ 1 + \frac{2 f q}{3(1 - q)} \right]^{-1}. \quad (3)$$

For $q = 0.2$ and $M_1 = 1.4 M_\odot$ (see §3) this gives

$$M_1 = 2.1 \times 10^{18} (1 - f) [1 + 0.14 f]^{-1} \text{g s}^{-1} \approx 3.3 \times 10^{-8} (1 - f) [1 + 0.14 f]^{-1} M_\odot \text{yr}^{-1}. \quad (4)$$

Note that the Eddington accretion rate for a 1 $M_\odot$ compact object is $M_{\text{Edd}} = 1.5 \times 10^{18} (0.1 / q) \text{g sec}^{-1}$, where $q$ is the radiative efficiency. The second term in square brackets of eq. (3) is small for $q < 0.7$. If, on the other hand, most of the mass loss occurs in the form of a wind from the secondary, the estimate for $M_1$ is much less well-constrained.

Since X 1822–371 is a LMXB, however, it is somewhat unlikely that the low-mass companion will have a very strong wind.

The above mass loss rate implies a change of the Roche lobe radius of the secondary, $R_2$, on comparatively short time scales as the orbital period evolution. Specifically, one can show that given the above assumptions

$$\frac{\dot{R}_2}{R_2} = -2 \frac{5}{6} q + \frac{f q}{3(1 + q)} \frac{M_2}{M_1}. \quad (5)$$

That is, for $q \approx 0.2$, the secondary’s Roche lobe radius is expanding, even for large mass loss via a wind, and therefore we expect strong mass transfer to be a short-lived phenomenon in this system. This conclusion is unaltered even if the (non-magnetic) wind mass loss occurs at radii as large as the disc circularization radius. If instead we postulate conservative mass transfer but an unspecified source of angular momentum loss (perhaps from magnetic braking and gravitational radiation) sufficiently large to lead to $R_2 = 0$, this implies an even larger mass transfer rate than discussed above ($M_1 \approx 10^{19}$ g s$^{-1}$ for a 1.4 $M_\odot$ primary), and also implies a characteristic angular momentum loss time scale of order $10^7$ years. We return to these considerations in §5.

2.2 Spectral Analysis

Given the uncertainties in the physical conditions in this system we felt it appropriate to keep spectral fitting to a phenomenological level. The fits we will present in the following are meant to represent just the essential features of the two physical cases outlined in the introduction: optically thick and optically thin geometries.

EXOSAT observations show an energy dependence of the modulation depth both for the sinusoidal component due to the accretion disc rim and the quasi-Gaussian eclipse due to the companion (Hellier & Mason 1989). Such a dependence might indicate a temperature stratification in the coronal region. We have tested the simultaneous RXTE and ASCA observations for such a trend by fitting a series of harmonics and a Gaussian to the X-ray lightcurves of the three instruments (PCA, SIS, and GIS). After inspection for convergence we truncated the fitting at the third harmonic. The fits confirm the trends reported by Hellier & Mason (1989). The fractional depth of the lowest order harmonic decreases with energy between 0.6 keV and 3 keV, and then rises again near the Fe Kα/Kβ region. The variation is small (of order 10%), but it is statistically significant. Both the fractional depth of the Gaussian and its width increase with energy. The product of the two (proportional to the fraction of the emission blocked by the secondary) actually varies significantly with energy, roughly by 50%, which we plot in Fig.1.

Due to the energy dependence of the modulation, some caution is in order when fitting global spectral models. We decided to divide the lightcurve into 5 parts (shown in Fig.5) labelled A (the eclipse) through E. The detailed spectral fitting we have performed was carried out for each of these phases to test the dependence of different parameters on orbital phase. We have also investigated the dependence of the PCA colours on phase. The strongest variations are found in the soft energy bands $[2.5–3.7 \text{ keV} / 3.7–5 \text{ keV} / 5–6.2 \text{ keV}]$, where we find variations of order 30% to 50%, with phase A being softest and phase D being hardest. In the more energetic bands $[5–6.2 \text{ keV} / 6.2–10.2 \text{ keV} / 6.2–10.2 \text{ keV}]$, the variation of colour with phase is weaker, i.e., of order 10%. These results are consistent with the analysis of BeppoSAX data by P00; however, the signal is not nearly as strong and as indicative as, for example, in the case of Her X-1. The strong phase-dependent behaviour in that case has been interpreted as being due to neutral hydrogen absorption and electron scattering in a large column depth medium (Stelzer et al. 1999).

As a starting point we fitted test models to the complete data set (not divided into phases). As with the previous analyses cited in the introduction, simple one-component models cannot produce a satisfactory fit— neither a single
blackbody, nor a thermal plasma, nor a cutoff power law adequately fit the data. Adding a second component can improve the fit significantly. We found that the combination of a disc blackbody (Mitsuda et al. 1984) with either a simple blackbody or a cutoff power law (plus a Gaussian to model the iron Kα line) did produce marginally acceptable fits (residuals are plotted in Fig. 3). However, better fits can be achieved with physically more plausible models, which are consistent with the strong constraints that light curve fitting puts on the geometry of the system, which we will outline below.

If the central object in X 1822–371 is in fact a neutron star, any thermal radiation from its surface is completely obscured by the accretion disc (Hellier & Mason 1989). The observed X-rays are produced either in the disc itself or in the corona. Lightcurve fitting indicates that the emission comes from a large extended source, and the (essentially required) power law component in the spectra supports the notion that the corona is the main radiation source. We based our spectral fitting on this assumption and investigated two possible, though not exclusive, spectral models, one with an optically thick corona and one with an optically thin corona.

The optically thick case: We expect the spectral signature of the hot corona to be of power law shape, with an exponential high energy cutoff produced by Comptonization, as is appropriate for many LMXBs (White & Stella 1988). (Here a cutoff at low energies would indicate a relatively cool corona.) If the corona is optically thick, the spectrum will not contain any component originating from the central object, as such radiation will have been completely reprocessed. The accretion disk is nearly edge on and its atmosphere will partially cover the coronal emission. To account for this effect, we used a model consisting of a partially absorbed cutoff power law and an iron line. The partial absorption is modelled by co-adding an unabsorbed and an absorbed cutoff powerlaw with equal parameters. The normalization of the absorbed component, however, is multiplied by a constant, const\textsubscript{cpl}, which is related to the absorption fraction, $f_{abs}$, by

$$f_{abs} \equiv \frac{\text{const}_{cpl}}{1 + \text{const}_{cpl}}. \quad (6)$$

The absorption column in the partial absorption model is treated as a free parameter, and we include both electron scattering and neutral hydrogen absorption modelled using the cross sections of Balucinska-Church & McCammon (1992). Our spectral model is, of course, a simplification because in any natural situation a range of absorbing columns will occur. Higher levels of detail, however, are not warranted given our understanding of this source and the limits of the X-ray data.

Having found a satisfactory overall spectral fit, we used the phase selected spectra to optimize the fits. We assumed that the physical parameters in the emitting region do not change from phase to phase and that the changes in the spectrum are entirely due to changes in obscuration of the corona both by the completely opaque disk and the partial absorption. We thus tied the powerlaw slope and the cutoff energy to be the same for all five phases, so that in the fitting process these parameters vary in unison. Similarly, we tied the iron line energy of all five phases together and, for lack of high spectral resolution from the PCA which dominates the

![Figure 2. Phase C spectrum and best fit models in the optically thick case. Top panel: spectrum and model components. Dotted line: PCA components; dashed line: SIS components. (a) Unabsorbed powerlaw; (b) absorbed powerlaw; (c) gaussian. From second panel down: residuals of different models. In sequential order downward: (1) disc blackbody plus cutoff power law plus narrow Gaussian at $\sim 6.4$ keV; (2) disc blackbody plus blackbody plus narrow Gaussian at $\sim 6.4$ keV; (3) partially absorbed cutoff powerlaw; (4) partially absorbed cutoff powerlaw plus iron line. The parameters for the fit in the bottom panel are shown in Table 2.](https://example.com/figure2.png)

statistics in this region, fixed the iron line width to 0.1 keV. The foreground absorption column was also tied together for all five phases. Having combined the two SIS data sets and the two GIS data sets, we were left with a total of 15 data sets, which we then fit simultaneously. The results of the joint fitting are presented in Table 2. The reduced $\chi^2$ is $\chi^2_{red} = 0.78$.

It is worth noting that there is a correlation between the power law normalization (overall count rate), the internal absorption column, and the absorption fraction, with the internal absorption column being greatest in the brightest phases. Note also that the equivalent width of the iron line is very large ($\sim 250$ eV, much larger than in the optically thin case). A more detailed interpretation of these results will follow in §5.

The optically thin case: What distinguishes the optically
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Best fit parameters for the 'optically thick model'. Again, the physical parameters are tied together (power law slope and cutoff, iron line energy), denoted by the symbol ‘\( \chi^2 \)’. The reduced \( \chi^2 \) of this fit is 0.74, with 9556 degrees of freedom. The iron line width was frozen at 0.1 keV.

We note that the lack of absorption in the best fit model is somewhat inconsistent with the predicted \textit{Colden} NH value. Forcing the hydrogen column to the \textit{Colden} value worsens the fit slightly, leading to residuals below 0.8 keV. Since the exact distance to X 1822−371 is unknown and the lack of partial absorption in the optically thin case is an idealization anyway, we decided to leave the clarification of this issue to \textit{Chandra} and XMM observations.

In both cases, the high energy end of the spectrum shows some systematic residuals, present also in the fits based on disc emission models. We suspect that at least some of this effect can be attributed to systematic errors in the RXTE response, in particular, differences in the high energy slopes of ASCA and RXTE. However, the \textit{Ginga} data reported by Hellier et al. (1992) also seem to show this hard excess, which would argue against a purely instrumental effect. In this paper we will not attempt a physical explanation of this feature. The failure of \textit{Astro-E} with its high energy capabilities is particularly unfortunate in this respect.

We then tried to determine the structure of the iron line. Since the sensitivity of the \textit{SIS} has been deteriorating, we decided to use only the 1993 \textit{SIS} dataset from the 1993 ASCA observation. We limited the fits to the energy range from 3−10 keV and approximated the continuum spectrum around the line by a cutoff power law. Two narrow lines produce the most significant improvement in \( \chi^2 \), from 587/458 to 421/454, in agreement with P00. The line energies are 6.4 keV and 7 keV, consistent with a cold Kα line and either Kβ or ionized Kα. The equivalent widths of the two lines are on the order of 80 eV and 40 eV respectively.

| Phase | \( N_{\text{Habs}} \) (\( \times 10^{22} \)) | \( E_{\text{line}} \) (keV) | \( \Gamma_{\text{pl}} \) | \( N_{\text{cpl}} \) (\( \times 10^{26} \)) | \( E_{\text{cpl}} \) (keV) | \( \chi^2_{\text{red}} \) |
|-------|-----------------|-----------------|------|-----------------|-----------------|-----------------|
| A     | 7.90±0.77       | 11.76±0.22      | 1.82±0.07 | 3.41±0.09 | 3.81±0.09 | 0.80±0.02 | 6.31±0.02 | 0.78, with 4656 degrees of freedom. The iron line width was frozen at 0.1 keV. |
| B     | 8.50±0.77       | 12.06±0.23      | 1.82±0.07 | 3.41±0.09 | 3.81±0.09 | 0.80±0.02 | 6.31±0.02 | 0.78, with 4656 degrees of freedom. The iron line width was frozen at 0.1 keV. |
| C     | 8.50±0.77       | 12.06±0.23      | 1.82±0.07 | 3.41±0.09 | 3.81±0.09 | 0.80±0.02 | 6.31±0.02 | 0.78, with 4656 degrees of freedom. The iron line width was frozen at 0.1 keV. |
| D     | 8.50±0.77       | 12.06±0.23      | 1.82±0.07 | 3.41±0.09 | 3.81±0.09 | 0.80±0.02 | 6.31±0.02 | 0.78, with 4656 degrees of freedom. The iron line width was frozen at 0.1 keV. |
| E     | 8.50±0.77       | 12.06±0.23      | 1.82±0.07 | 3.41±0.09 | 3.81±0.09 | 0.80±0.02 | 6.31±0.02 | 0.78, with 4656 degrees of freedom. The iron line width was frozen at 0.1 keV. |

\textbf{Table 2.} Best fit parameters for the ‘optically thick model’. Again, the physical parameters are tied together (power law slope and cutoff, iron line energy), denoted by the symbol ‘\( \chi^2 \)’. The reduced \( \chi^2 \) of this fit is 0.74, with 9556 degrees of freedom. The iron line width was frozen at 0.1 keV.

3 MODELLING THE LIGHTCURVE

Models of the X 1822−371 lightcurve, for both the optical and X-ray energy bands, have been presented by White & Holt (1982), Mason & Córdova (1982a), and Hellier &
Table 3. Best fit parameters for the optically thin model. Physical parameters (blackbody temperature, power law slope and cutoff, plasma temperature, and iron line energy) are tied to stay constant as a function of phase, defined by the symbol . The reduced $\chi^2$ for this fit is $\chi^2 = 674$, with 4655 degrees of freedom. We have frozen the iron line width to $0.1 \, \text{keV}$. Similarly, redshift and metallicity of the Raymond-Smith component were frozen to their canonical values (0 and 1 respectively).

| Phase | $N_{\text{H}}$ (10$^{22}$ cm$^{-2}$) | $\Gamma$ | $kT_{\text{BB}}$ (keV) | $E_{\text{Fe}}$ (keV) |
|-------|----------------------------------|--------|------------------------|----------------------|
| A     | 0.000 ± 0.000                   | 1.39 ± 0.000 | 0.14 ± 0.000          | 0.04 ± 0.000        |
| B     | 2.28 ± 0.02                    | 2.04 ± 0.05 | 1.43 ± 0.03           | 0.04 ± 0.02         |
| C     | 1.05 ± 0.03                    | 1.70 ± 0.01 | 0.77 ± 0.03           | 0.04 ± 0.00         |
| D     | 1.58 ± 0.03                     | 1.70 ± 0.01 | 0.77 ± 0.03           | 0.04 ± 0.00         |
| E     | 1.02 ± 0.03                     | 1.70 ± 0.01 | 0.77 ± 0.03           | 0.04 ± 0.00         |
disc rim profile is then linearly extrapolated at intermediate phases. Fit parameters for these models have included the radius of the X-ray emitting corona, usually assumed spherical for simplicity, the heights and phases of the rim nodes, the mass of the compact object, and the inclination angle of the system with respect to our line of sight (see Hellier & Mason 1989).

Here we elaborate upon these models in two ways. First, due to the excellent statistics of RXTE, we are able to divide the RXTE lightcurves into five distinct energy bands covering PCA pha channels 8–11, 12–15, 16–19, 20–27, and 28–32 (2.9–4.4 keV, 4.4–5.8 keV, 5.8–7.2 keV, 7.2–10.2 keV, and 10.2–12.0 keV, respectively). We fit each of these energy band lightcurves simultaneously. Second, we model both an optically thin and an optically thick spherical corona. Specifically, we model the X-ray emission via a uniform emissivity or a uniform surface brightness. We do not expect (and as we confirm below; see also Hellier & Mason 1989) strongly different values between the two cases. Given a completely edge-on viewing angle, for a given disc rim height the fraction of emission that is obscured and the emission-weighted mean height of the unobscured radiation are nearly identical for both uniform surface brightness and uniform emissivity. In our fits, we allow both the overall flux normalization and the radius of the sphere to vary for each energy band; however, the disc rim parameters (radius of the disc, $R_{\text{rim}}$, node heights, $H$, and node phases, $\phi$) are fixed. Additional fit parameters are the mass of the compact object ($M_1$) and the inclination of the system with respect to our line of sight ($i$).

In part these parameters are determined by utilizing the fact that $X_{1822–371}$ has a known binary period of $P = 5.57$ hr and a measured projected primary orbital velocity of $K_1 = 70$ km s$^{-1}$ (Mason et al. 1982; Cowley et al. 1982). We highlight the systematic uncertainties in our fit parameters by varying this latter parameter by +30 km s$^{-1}$ (see Cowley et al. 1982). Furthermore, we search for model fits with $M_1 \sim 0.3, 1.4$ and 2.5 $M_\odot$. That is, we fit models for a ‘white dwarf’, ‘canonical neutron star’, and ‘low mass black hole’ primary. The latter primary mass yields a secondary mass consistent with Roche lobe overflow from a main sequence star (see below).

In order to better interpret the results of our fits, we first present estimates of the characteristic accretion system size and mass scales. Defining the secondary to primary mass ratio, $q \equiv M_2/M_1$, Newton’s laws give $q \approx 0.21$ for $M_1 = 1.4 M_\odot$, $K_1 = 70$ km s$^{-1}$, and $i = 85^\circ$. Henceforth, these parameter values shall be referred to as the ‘nominal parameters’. As noted by Mason et al. (1982), this mass ratio is roughly half that expected from the mass-period relationship for a lower main sequence secondary. If instead we choose $M_1 = 2.5 M_\odot$, $K_1 = 100$ km s$^{-1}$, and $i = 85^\circ$, one obtains a secondary mass of $M_2 \approx 0.62 M_\odot$, as one would expect for the period-mass relationship of a main sequence star (Frank et al. 1992). The above system parameters yield binary separations of $a \approx 1.3–1.6 \times 10^{13}$ cm, respectively. Over the parameter ranges of interest to us, $q$ varies roughly as $(K_1 / \sin i) M_1^{-1/3}$, and the binary separation weakly varies as $(1 + q^{1/3}) M_1^{1/3}$.

The disc circularization radius can be determined via the approximation

$$ R_{\text{circ}} = (1 + q)(0.5 - 0.227 \log q)^{1/3} a $$

(Frank et al. 1992), where for the nominal parameters $R_{\text{circ}} \approx 0.22 a \approx 2.9 \times 10^{10}$ cm. As a fraction of the binary separation, this ratio is fairly constant for the parameters of concern to us. The disc tidal truncation radius is approximately given by $R_T \approx 0.9 R_1$, where $R_1$ is the Roche lobe radius of the primary. Approximating this radius (Eggleton 1983) as

$$ R_1 \approx \frac{0.49q^{-2/3}}{0.6q^{-2/3} + \ln(1 + q^{-1/3})} $$

yields $R_T \approx 0.47 a \approx 6.1 \times 10^{10}$ cm for the nominal parameters. Again, expressed as a fraction of the binary separation, this radius is relatively constant for the parameters of interest to us.

Equation 8, with $q$ replaced by $q^{-1}$, also yields $R_2/a$ ($\approx 0.22$ for the nominal parameters), where $R_2$ is the Roche lobe radius of the secondary. For a near edge on system with a brief (relative to the orbital period) eclipse, $R_2/a$ is approximately proportional to the fraction of the binary period that can be eclipsed by the secondary. This fraction is roughly proportional to $q^{1/3} \propto M_2^{-1/3}(K_1 / \sin i)^{1/3}$. As the duration of the eclipse is a fixed fraction of the binary orbital period, we therefore expect the coronal radius, expressed as a fraction of the binary separation, to be weakly dependent upon $K_1 / \sin i$ and almost completely independent of $M_1$ (see also Mason & Córdova 1982). As we show below, we indeed can fit a relatively wide range for $M_1*$. The mass ratio, $q$, however, is more tightly constrained by the lightcurve fits.

We divide the lightcurves into 50 phase bins in each energy band. In lieu of statistical errors, which were very small given the large effective area of RXTE, a systematic error of 4.2% was added to each phase bin. This represented the average variance of the lightcurve from orbit to orbit over the $X_{1822–371}$ period. (Approximately four orbital periods were measured in part or in whole.) For the optically thin case, the corona was divided into 6 evenly spaced radial zones, 50 evenly spaced zones in the azimuthal angle, $\phi$, and 50 zones evenly spaced in $\mu \equiv \cos \theta$ in the polar angular direction, $\theta$. The optically thick corona had $50 \times 50$ evenly spaced zones in $\phi$ and $\mu$. We assumed a disc rim with 9 and 2 nodes symmetrically placed above and below the disc mid-plane. Ray tracing was performed to determine whether emission from a given coronal element intercepted the disc rim. Near zero phase, the blink subroutine from Keith Horne’s eclipse mapping code (Horne 1985) was used to determine if the secondary was blocking the line of sight to the emission element. In all, there were 31 fit parameters (primary mass, system inclination, 5 coronal radii and emissivities/surface brightnesses, disc rim radius, and 9 node heights and phases). For the fits, all energy bands were weighted equally, and the amoeba subroutine from Press et al. (1992) was used in the $\chi^2$ minimization. Fit results are presented in Tables 4 and 5.

Fig. 5 shows the best fit optically thick corona model for the 4.4–5.8 keV energy band, as well as

* If we insist that the (main sequence) radius of the secondary not be greater than $R_2$, then we require $M_1 \leq 2.5$. Hence we only consider primary masses of $\approx 0.3, 1.4$, and 2.5 $M_\odot$.
Table 4. System and Coronal Parameters for Fits to the X 1822–371 RXTE Lightcurves. All length scales are in units of the binary separation, $a$. $R_{c,\phi}$ is the radius of the optically thin or thick, uniformly emitting corona for RXTE pha channels $a$–$b$. $R_{c,180}$ is the radius of the obscuring rim. $M_1$ is the mass of the central compact object, and $i$ is the angle of the normal to the binary orbital plane with respect to our line of sight. Values given are assuming a projected primary velocity of $K_1$.

| Model | $M_1$ (M$_\odot$) | $K_1$ (km s$^{-1}$) | $i$ (°) | $R_{c,1}$ | $R_{c,2}$ | $R_{c,3}$ | $R_{c,4}$ | $R_{c,5}$ | $R_{c,6}$ | $R_{c,7}$ | $R_{c,8}$ | $\chi^2$/dof |
|-------|-------------------|----------------------|--------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-------------|
| Thin  | 0.32              | 70                   | 80.7   | 0.220     | 0.216     | 0.210     | 0.211     | 0.211     | 0.38       | 188/219   |            |             |
| Thin  | 1.40              | 70                   | 83.4   | 0.219     | 0.217     | 0.216     | 0.216     | 0.215     | 0.41       | 154/219   |            |             |
| Thin  | 2.47              | 100                  | 82.5   | 0.220     | 0.216     | 0.213     | 0.213     | 0.212     | 0.40       | 175/219   |            |             |
| Thick | 0.31              | 70                   | 81.1   | 0.216     | 0.213     | 0.209     | 0.210     | 0.210     | 0.40       | 181/219   |            |             |
| Thick | 1.38              | 70                   | 83.7   | 0.215     | 0.214     | 0.213     | 0.213     | 0.213     | 0.39       | 180/219   |            |             |
| Thick | 2.48              | 100                  | 83.0   | 0.216     | 0.213     | 0.212     | 0.212     | 0.212     | 0.41       | 180/219   |            |             |

Table 5. Disc Rim Parameters for Fits to the X 1822–371 RXTE Lightcurves. All length scales are in units of the binary separation, $a$, and phases are in units of the binary phase. $\phi$ and $H$ are, respectively, the phase and height of disc rim nodes $N_1$–$N_3$. Rim heights inbetween the nodes are determined by linear interpolation. Values given are assuming a projected primary velocity of $K_1$.

| Model | $M_1$ (M$_\odot$) | $K_1$ (km s$^{-1}$) | $N_1$ | $N_2$ | $N_3$ | $N_4$ | $N_5$ | $N_6$ | $N_7$ | $N_8$ | $N_9$ |
|-------|-------------------|----------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Thin  | 0.32              | 70                   | 0.111 | 0.295 | 0.321 | 0.408 | 0.526 | 0.750 | 0.813 | 0.934 | 0.943 |
|       |                   |                      | $H$   | 0.110 | 0.093 | 0.075 | 0.102 | 0.099 | 0.136 | 0.132 | 0.109 | 0.108 |
| Thin  | 1.40              | 70                   | 0.107 | 0.202 | 0.317 | 0.399 | 0.564 | 0.741 | 0.846 | 0.882 | 0.938 |
|       |                   |                      | $H$   | 0.104 | 0.105 | 0.080 | 0.097 | 0.103 | 0.129 | 0.132 | 0.096 | 0.117 |
| Thin  | 2.47              | 100                  | 0.124 | 0.299 | 0.317 | 0.413 | 0.537 | 0.768 | 0.830 | 0.889 | 0.907 |
|       |                   |                      | $H$   | 0.106 | 0.090 | 0.078 | 0.099 | 0.100 | 0.133 | 0.132 | 0.100 | 0.112 |
| Thick | 0.31              | 70                   | 0.112 | 0.291 | 0.323 | 0.410 | 0.535 | 0.750 | 0.831 | 0.924 | 0.928 |
|       |                   |                      | $H$   | 0.111 | 0.090 | 0.074 | 0.101 | 0.100 | 0.139 | 0.134 | 0.103 | 0.108 |
| Thick | 1.38              | 70                   | 0.103 | 0.292 | 0.359 | 0.441 | 0.553 | 0.756 | 0.828 | 0.896 | 0.911 |
|       |                   |                      | $H$   | 0.111 | 0.088 | 0.082 | 0.103 | 0.101 | 0.137 | 0.132 | 0.104 | 0.112 |
| Thick | 2.48              | 100                  | 0.111 | 0.296 | 0.343 | 0.419 | 0.537 | 0.765 | 0.819 | 0.922 | 0.930 |
|       |                   |                      | $H$   | 0.109 | 0.088 | 0.079 | 0.100 | 0.101 | 0.137 | 0.132 | 0.104 | 0.110 |

The fitted disc rim profiles for both the optically thick and thin models, both for $M_1 \sim 1.4$ M$_\odot$, $K_1 = 70$ km s$^{-1}$. (Animations of the fits can be viewed at http://rocinante.colorado.edu/~heinzs/1822/.) We note that using fewer coronal grid points did not adequately resolve the coronal emission; however, numerical discreteness in the fitting process led to uncertainties of $\Delta \chi^2 \approx 2$ in any fits with a greater number of coronal grid points. In Table 4 we therefore only present the systematic errors associated with varying the projected primary velocity, $K_1$, between 70 and 100 km s$^{-1}$ and from searching for $\chi^2$ minima near primary masses of 0.3, 1.4, and 2.5 M$_\odot$. We also experimented with varying the number of nodes in the fit; however, 9 nodes were sufficient to produce a reduced $\chi^2 \lesssim 1$.

Both the optically thick and optically thin coronal models fit the data nearly equally well, with $\chi^2$ ranging from 154–188 for 219 degrees of freedom. Although there is a slight preference for an optically thin corona with $M_1 \approx 1.4$ M$_\odot$, given the simplicity of our assumptions we do not consider these differences to be strongly significant.

Most of the fits showed a weak trend for the coronal radius to decrease with energy, as would be expected from the energy-dependent fractional modulation shown in Fig. 1. The fractional change in the coronal radii was as large as 5%; however, this is still somewhat smaller than the ~10% found in the two energy channel (1–6 keV and 6–30 keV) Ginga data fits of Hellier et al. (1992). The other size scale parameters are consistent with previous models of the lightcurve (White & Holt 1982; Mason & Córdova 1982a; Hellier & Mason 1989). Specifically, the disc rim height shows a minimum near phase 0.3–0.35, and a maximum near phase 0.75–0.85. The disc rim height is $\approx 0.1a \approx 1.5 \times 10^{10}$ cm. The radius of the disc rim is consistent with being at the tidal truncation radius, which is reasonable if the disc rim is due to the interaction of the secondary’s accretion stream with the disc (see, for example, Armitage & Livio 1996, 1998, and references therein). The coronal radii are all $\approx 0.2a \approx 3 \times 10^{19}$ cm, i.e. consistent with the corona extending all the way to the disc circularization radius.

We find a system inclination of $i \approx 81^\circ$–84°, which is also consistent with previous models of the lightcurve (Hellier & Mason 1989). As expected from the analysis discussed above, the fits for $M_1 \approx 0.3$, 1.4, and 2.5 M$_\odot$ were nearly identical. Thus, based upon the lightcurve analysis...
alone, it is impossible to determine whether X 1822–371 is a white dwarf, neutron star, or a black hole. Further observations, especially any that can independently measure the velocity of the secondary, are required to break the degeneracy in the primary mass values. We note that to this end, Harlaftis et al. (1997) place a lower limit on the companion velocity of $K_{2} \approx 25\text{ km s}^{-1}$. If the lower end of this value is accurate and $K_{1} = 70\text{ km s}^{-1}$, then $q = K_{1}/K_{2} \approx 0.3$ (consistent with the above estimates) and $M_{1} + M_{2} \approx 0.6 M_{\odot} \propto (K_{1} + K_{2})^{2}$, i.e., X 1822–371 is a white dwarf system.

### 4 VARIABILITY ANALYSIS

Extremely high time resolution data were available from the RXTE observations. Accordingly, we created lightcurves with $0.5\text{ s}$ resolution. We chose three energy bands covering PCA pha channels 5–10, 16–19, and 28–41 (1.8–4 keV, 5.8–7.2 keV, and 10.2–15.3 keV respectively). These energy bands were chosen to represent a low energy band, an Fe Kα/β band, and a high energy band. Energies higher than $\approx 15\text{ keV}$ were background dominated.

We consider three measures of the variability: the power spectral density (PSD) in each energy band, and the Fourier frequency-dependent time lags and coherence function between variability in different energy bands. A discussion of Fourier techniques in specific, and timing analysis in general, has been presented by van der Klis (1989). Here we apply these Fourier analysis techniques in the same manner as for our RXTE observations of Cyg X–1 (Nowak et al. 1999). Specifically, we used the same techniques for estimating: deadtime corrections (Zhang et al. 1995; Zhang & Jahoda 1996); the error bars and Poisson noise levels of the PSD (Leahy et al. 1983; van der Klis 1989); the error bars and noise levels for the coherence function (Bendat & Pierson 1986; Vaughan & Nowak 1997); and the error bars and noise levels for the Fourier frequency-dependent time lag between hard and soft photon variability (Bendat & Pierson 1986; Nowak et al. 1999). Results of these analyses for the lowest and highest energy bands are presented in Fig. 6. In this figure, the PSDs are normalized according to Belloni & Hasinger (1990) wherein integrating over Fourier frequency yields the mean square variability relative to the square of the mean of the lightcurve.

All three PSDs had roughly comparable shapes and amplitudes. Specifically, they show evidence for a rise in power at frequencies $\lesssim 3 \times 10^{-3}\text{ Hz}$, broad peaks at $f \sim 0.02$ and 0.08 Hz, and reasonably sharp declines for $f \gtrsim 0.1\text{ Hz}$. No power in excess of noise is seen above $\approx 0.3\text{ Hz}$. The root mean square (rms) variability increases from soft to hard energies. From softest to hardest energy bands, the rms variabilities are $8\%/7\%, 10\%/8\%,$ and $11\%/9\%$ over the $10^{-3}$–$0.3\text{ Hz}/10^{-2}$–$0.3\text{ Hz}$ range. The up-turn at low frequency is most likely due to variability associated with the orbital time scales. (Due to low count rates, phase resolved variability studies are very difficult.) The coherence at $f \lesssim 10^{-2}\text{ Hz}$ being slightly lower than that at higher frequencies might be related to an admixture of intrinsic variability of the corona with variability associated with the orbital period, although overall the variability between the highest and lowest energy bands is well-correlated. We note that 7–9% rms variability in the $10^{-2}$–$0.3\text{ Hz}$ range is consistent with the variability seen in both low ($\lesssim 5\% L_{\text{Edd}}$) and high ($\gtrsim 30\% L_{\text{Edd}}$) fractional Eddington luminosity neutron star and black hole sources.

The lack of high frequency variability may be due to scattering over large distances and/or optical depths (see Nowak & Vaughan 1996, and references therein). Specifically, if the variable lightcurve is first passed through a scattering medium of optical depth $\tau$ and size $D$, one expects a cutoff in the power spectrum at a frequency, $f_{\text{cut}}$, given by

$$2\pi f_{\text{cut}} \approx \min \left[ \frac{c}{\tau D}, \frac{c}{D} \right].$$

Thus, given $D \sim R_{c} \sim 0.2a \sim 3 \times 10^{10}\text{ cm}$, the cutoff fre-
Scattering may also lead to the observed variability lags. Over the narrow frequency region for which one can obtain lag measurements, the softest energy band is seen to lag the hardest energy band by \( \approx 1 \text{s} \). (Note, the statistics were not sufficient to measure accurately the time lag of the variability in the middle energy band with respect to that in either of the other two energy bands.) Such a lag is consistent with a central X-ray source being reprocessed downward in energy by scattering within a corona of radius/scattering path length of order \( 3 \times 10^{10} \text{ cm} \), consistent with the fits of §3.

5 DISCUSSION

Having laid out the observational facts, we now turn to their interpretation. Several key issues about X 1822–371 have surfaced in the earlier sections, which we will now address, along with some open questions which relate to earlier studies of this object.

5.1 Detailed Spectral Fitting

As we have shown, several fundamentally different models can explain the ASCA and RXTE spectra almost equally well. While formally satisfactory, the spectra we presented in §2.2 still show some systematic residues, which could be removed by addition of features like absorption edges and lines. For example, P00 argue that there is clear evidence for an edge around 1.3 keV. We do see a hint of such an effect, especially in the optically thick case, but it is not clear if the origin is really an absorption edge. The same feature might be produced by an emission line complex at 1 keV (as demonstrated in the optically thin case, where the addition of a Raymond-Smith plasma removed the systematic residues at the low energy end). We also note that the edge in the fits by P00 fails very close to the position where two major spectral components (blackbody and Comptonization spectrum) cross in their fits.

Similarly, the structure of the iron line region is all but clear. As remarked by P00, the ratio of the two narrow lines we fit to the data is off from the theoretical value expected for Kα to Kβ, but ionized line emission could explain this fact. In the optically thin models the ionization parameter in the corona is much larger than one, which would strengthen such an argument. Both of these questions will undoubtedly be answered by upcoming XMM-Newton and Chandra observations.

\[ f_{\text{cut}} \approx 0.2 \text{ min}[\tau^{-1}, 1] \text{ Hz}^{\dagger} \], consistent with what is observed here.

\[ 2\pi f_{\text{cut}} \approx c/D \], even for \( \tau \gg 1 \). This is because for such a situation, fixing the energy band of the observed output is essentially fixing the number of scatters that the observed photons have undergone, and therefore narrows the dispersion in the photon arrival times. See Nowak & Vaughan (1996), and references therein.

\[ f_{\text{cut}} \approx 0.2 \text{ min}[\tau^{-1}, 1] \text{ Hz}^{\dagger} \]

5.2 Optically Thick vs. Thin

Both in spectral modelling and in fitting the light curve, we used two general models, based on whether the corona is optically thick or thin. We found that both light curve and spectrum are degenerate with respect to this distinction, and optically thick and thin models reproduce these data equally well. We will now discuss the physical interpretation of the two cases (see also §5.4).

- In the optically thick case we modelled the spectrum as a partially absorbed power law, produced by reprocessed radiation from the corona, passing through a column of cold gas (the atmosphere of the outer disc). From the spectral fit we can then deduce the covering fraction and optical depth of the partial absorber. These numbers are given in Table 2.

We can understand the above mentioned correlation between the partial absorption column, the absorption fraction, and the overall flux through the following picture: the X-rays originate from an approximately spherical corona (at uniform surface brightness). The accretion disc rim is completely opaque and responsible for most of the modulation in the light curve, due to differences in its height (and thus its covering fraction). Above the accretion disc, an atmosphere of cold gas absorbs/scatters a fraction of the light from the corona behind it. The geometric covering fraction would roughly be given by the ratio of the atmosphere’s scale height to the corona radius. As the rim height changes through the binary phases, the covering fraction of the partial absorber also changes (see Table 2).

Higher latitudes of the corona are relatively less absorbed, thus for binary phases where the the disc rim is higher, the ratio of unabsorbed to absorbed coronal flux will be greater. At the same time, the average column depth of the absorber should be smaller, since the gas density is lower at higher latitudes. The trend in Fig. 1 can also be understood this way: the absorbed component of the power law contributes primarily hard X-rays to the spectrum. Since this part of the spectrum originates at low latitudes, it is most affected by obscuration, thus the larger modulation depths at high energies. The implied scale heights and column depths of Table 2 are consistent with what would be expected from an X-ray heated atmosphere above the disc between the edge of the corona and the disc rim (White & Holt 1982).

The fact that we only see a small fraction of the luminosity inferred from the orbital evolution can be explained if the corona is optically thick to scattering while relatively optically thin to absorption. In that case it will act as a mirror and transmit only a fraction \((1 + \tau)^{-1}\) of the incident radiation. For a ratio of observed to inferred luminosity of \( \sim 200 \), modulo a geometric covering factor, this would imply an optical depth of \( \tau \lesssim 200 \) (which justifies the assumption of an optically thick corona in this model). As we will discuss below (see §5.4), a large fraction of the energy could also leave the system in a wind (Adiabatic Inflow-Outflow Solution, ADIOS; Blandford & Begelman 1999) or, in the case of a black hole primary, disappear down the horizon (optically thick Advection Dominated Accretion Flow, ADAF; Narayan & Yi 1994).

Table 2 shows that the equivalent widths of the iron lines are rather large, of order 250 eV. A simple estimate of the expected EW produced solely within the partial absorber by the incident coronal spectrum is of the order of 50 eV.
Uncertainties in the metallicity or the geometry of the system (i.e., if the partial absorber is subject to a larger flux than seen by the observer) might account for such a discrepancy. Note also that the partial covering model introduces an iron absorption edge at 7.1 keV, which is leading in part to the large fitted equivalent widths. As noted by P00 and references therein, the line ratios are still problematic if the higher energy line is an Fe Kβ line, as opposed to ionized Fe Kα. Models of resonant scattering of the Fe Kα line by the partial absorber in the outer disc rim region may help explain some of this discrepancy. Finally, we note that the optically thick corona itself could well be the origin of strong iron line emission.

- The key question for the optically thin case is whether or not there is unambiguous evidence for blackbody emission from the surface of the compact object that is scattered into our line of sight. Related to this is the question of whether or not there is clear evidence for coronal line emission, i.e. a thermal plasma component. As the optically thick model, with partial absorption, fits the spectrum adequately, evidence for these components cannot be claimed to be unambiguous. Ignoring the partial covering (due to the limits of our data and models), however, these components are seen to be allowed in the fits, thus there absence cannot be definitively shown either.

Assuming the optically thin scenario to be correct, the X-ray emission is again produced in the corona. The blackbody part of the continuum is produced either on the neutron star surface (if the central object is in fact a neutron star) or the inner disc, and is then scattered into our line of sight by the corona. The power law part of the spectrum stems from radiation that is Comptonized in the corona. If the corona is optically thin, the fraction of the total X-ray luminosity that reaches the observer is \( \approx \tau \). The optical depth of the corona would thus be \( \tau \gtrsim 1/200 \), once again modulo the geometric covering factor. We note again that a fraction of the accretion energy might be carried away in a wind or advected (in the case of a black hole primary).

Note that the modulation seen in the power law is stronger than the modulation seen in the blackbody. We can interpret this dependence geometrically if we further postulate that the power law emission is produced at lower coronal latitudes, in which case a larger fraction of it would be subject to obscuration both by the rim and the companion. The variations shown in Fig. 1 would be natural in such a scenario, since the black body component emanates from the whole corona, is relatively less modulated, and contributes most strongly at low and intermediate energies. Again, however, a partial covering model may be applicable for the optically thin case as well as for the optically thick case.

The fitted iron line in this case is weaker than for the optically thick case, but due to the neglect of partial absorption this model does not contain an intrinsic absorption feature around 7 keV. All other remarks with respect to the line strength in the optically thick case hold here too.

Both these models can explain the basic features of light curve and spectrum, we therefore have no way to chose one over the other. In fact, reality might fall in between these two cases. One might imagine a model where the optical depth of the corona decreases with height. We would thus see scattered blackbody radiation from high latitudes and a partially absorbed power law from the optically thick parts closer to the disc. Hopefully, future X-ray and optical observations will resolve this degeneracy.
decrease the inferred distance (Mason & Córdova 1982a) and luminosity by a factor of ~ 0.6 and ~ 0.4, respectively, we would still require that we are viewing of order 100% of the accretion luminosity despite the presence of a scattering corona and the near edge-on inclination of the system. Second is the implied mass of the secondary, \( M_2 \approx 0.06 M_\odot \), which is slightly small given the then inferred Roche lobe radius of the secondary, \( R_2 \approx 2 \times 10^{10} \text{cm} \approx 0.3 R_\odot \). Again we note, however, that if the lower values of \( K_1 = 70 \text{km s}^{-1} \) and \( K_2 = 225 \text{km s}^{-1} \) are correct (Harlaftis et al. 1997), than a white dwarf primary is the preferred model.

Of the other two possibilities, neutron star or black hole, there is little to distinguish between them. Given the edge-on inclination and the implied large scattering paths, it is not surprising that we do not detect any variability associated with a neutron star spin period, as discussed in §4. Furthermore, given little or no mass loss, the implied accretion rate onto the neutron star would be sufficient to suppress any Type I bursting behaviour (Bildsten 1995, and references therein). We therefore expect a neutron star and low mass black hole to look nearly identical. Distinguishing between these two scenarios, therefore, will require a combination of more careful observations of the secondary and identifying a plausible evolutionary scenario for this system.

5.4 Winds, Advection Domination, and the Evolutionary History of X 1822–371

As discussed in §2.1, the implied mass transfer time scale is \( \tau_{\text{mt}} \approx 10^7 \text{years} \), which is compatible with mass transfer on a thermal time scale (see Kalogera & Webbink 1996, and references therein). One interesting possibility is that we are viewing the X 1822–371 system towards the end of a thermal time scale mass transfer phase (Kalogera & Webbink 1996). Specific scenarios have been discussed for Cyg X-2 (King & Begelman 1999; King & Begelman 1999) and SS 433 (King et al. 2000). At the onset of mass transfer the system begins with a mass ratio \( q > 1 \). As the secondary loses mass, both the binary separation and the secondary Roche lobe shrink. A common envelope phase is avoided by strong mass loss from the primary, perhaps in an advection dominated accretion phase characterized by a strong wind emanating from large radii (King & Begelman 1999; King et al. 2000). Even as \( q \) decreases below unity, mass transfer can continue to be driven on the thermal time scale. For the Cyg X-2 system (known to be a neutron star primary; Smale 1998), it is hypothesised that the system began with an \( \approx 3.5 M_\odot \) secondary, but now shows an \( \approx 0.5 M_\odot \) secondary with a radius \( \approx 7 R_\odot \) (King & Ritter 1999).

The above mentioned systems, however, cannot be exactly analogous to that of the X 1822–371 system. Cyg X-2, for example, has a 9.84 day orbital period and a secondary luminosity of \( \approx 150 L_\odot \), both far larger than in X 1822–371. In the optical bands, aside from X-ray heating of the secondary, it has traditionally been assumed that the X 1822–371 emission is dominated by the accretion disc and disc rim, with the total optical luminosity being \( L_{\text{opt}} \approx 10 L_\odot \) (Mason & Córdova 1982a). Likewise, models of the UV emission have been presumed to be dominated by the disc and the corona (Mason & Córdova 1982b), although perhaps the far UV allows the greatest room for significant contributions from the secondary. In addition, obtaining the currently observed 5.57 hr orbital period via mass transfer alone requires that during the earlier epoch wherein \( 0.2 < q < 1 \), the orbital period was even shorter. The current 5.57 hr orbital period might require an extended epoch of magnetic braking of the secondary (Rappaport et al. 1983; Taam 1983; Pylyser & Savonije 1988; and references therein).

As discussed in the above references, magnetic braking is expected only to be effective for secondaries that do not have a fully convective envelope. Although strong mass transfer rates are possible before mass loss leads to such an envelope, this epoch is only expected to last \( 10^6–10^7 \) years (Rappaport et al. 1983). This is consistent with our previous estimates of the lifetime of the X 1822–371 system. We note that during this strong mass transfer phase, one generally expects the secondary to exceed its main sequence radius (Taam 1983; Kalogera & Webbink 1996). If we define the ratio of the secondary’s Roche lobe radius to its main sequence radius as \( \mathcal{R} \), then given the discussion of §3 we can approximate the mass of the primary as

\[
M_1 \approx 3.0 \mathcal{R}^{-9/4} \left( \frac{K_1/\sin i}{70 \text{ km s}^{-1}/\sin 85^\circ} \right)^{-2/3}.
\]

Thus, \( \mathcal{R} \gtrsim 1.2 \) allows for a neutron star mass \( \lesssim 2 M_\odot \).

Finally we note that in addition to any mass loss associated with magnetic braking, further strong mass loss from such a system as suggested by King & Begelman (1999) leads to another explanation (in addition to postulating that the coronal optical depth \( \tau \ll 1 \) or \( \tau \gg 1 \)) for the fact that we observe only \( \approx 10^{-2} \) of the accretion luminosity inferred for an efficiency of \( \eta \approx 10\% \). ‘ADIOS’ models wherein most of the accreted mass never reaches the surface or event horizon of the primary (Blandford & Begelman 1999; King & Ritter 1999) allow for either a neutron star or black hole primary. In such a scenario, the energy of viscous dissipation is not efficiently radiated away from the system and must be carried away via a wind. Viscous dissipation occurs out to the circularization radius, which is the inferred radius of the corona from our fits of §3, and thus dissipation may in part be responsible for the presence of the corona (which in this case could be an ADIOS wind).

6 CONCLUSIONS

We have presented observations of the low mass X-ray binary X 1822–371 taken with both RXTE and ASCA. We considered two broad band fits, which we took as approximately representing ‘optically thick’ and ‘optically thin’ coronal emission. Either model fit the data nearly equally well. Likewise, the X-ray lightcurves folded on the orbital period were also equally well-fit by optically thick or thin models, and furthermore these fits could not distinguish among a white dwarf, neutron star, or black hole primary. High spectral resolution ASCA data revealed complex structure in the Fe Kα/Kβ region, consisting of possibly two lines. These latter features might be related to obscuring material between the edge of the corona and the disc rim, and also possibly related to emission from any optically thick regions of the corona.

The spectral ambiguities of the line region will likely be resolved by upcoming high resolution observations with
XMM-Newton and Chandra. The nature of the primary, however, will likely not be revealed by these observations. As discussed above, understanding the nature of the primary will in large part depend upon further observations of the secondary, and depend upon identifying a plausible evolutionary scenario for the X 1822–371 system.

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APPENDIX A: DATA ANALYSIS METHODOLOGY

A1 RXTE Data Analysis

We extracted data from both pointed instruments on RXTE, the Proportional Counter Array, PCA, and the High Energy X-ray Timing Experiment, HXTE. X 1822–371, however, is both very faint and very soft, therefore we only spectrally fit data from the PCA instrument. The RXTE data were analyzed using the same procedure as that for our analysis of the spectrum of GX 339–4 (Wilms et al. 1999b). Specifically, all RXTE results in this paper were obtained using the standard RXTE data analysis software, ftools version 4.2, and response matrix v3.1. Data selection criteria were that the source elevation was larger than 10° above the earth limb and data measured within 30 minutes of passages of the South Atlantic Anomaly or during times of high particle background (as expressed by the “electron ratio” being greater than 0.1) were ignored. To increase the signal to noise level of the data, we restricted the analysis to the first anode layer of the proportional counter units (PCUs) where most source photons are detected (the particle background is almost independent of the anode layer), and we combined the data from all five PCUs. We only used data where all five PCUs were turned on, which was nearly the entire observation.

For spectral fitting, we limited the energy range of the PCA data from 3 to 30 keV. To take into account the calibration uncertainty of the PCA we applied the channel dependent systematic uncertainties described by Wilms et al. (1999b). These uncertainties were determined from a power-law fit to an observation of the Crab nebula and pulsar taking into account all anode chains; however, they do also provide a good estimate for the first anode layer only since most of the photons are detected in this layer. Background subtraction of the PCA data was performed using the ‘SkyVLE’ model, as for our previous studies of GX 339–4 (Wilms et al. 1999a).

A2 ASCA Data Extraction

We extracted data from the two solid state detectors (SIS0, SIS1) and the two gas detectors (GIS2, GIS3) onboard ASCA by using the standard ftools as described in the ASCA Data Reduction Guide (Day et al. 1998). We chose circular extraction regions with radii of ≈ 4 arcmin for the SIS detectors, and ≈ 6 arcmin for the GIS detectors. We excluded approximately the central 1 arcmin to avoid the possibility of photon pileup. We used the sisclean and gisclean tools (with default values) to remove hot and flickering pixels. We filtered the data with the strict cleaning criteria outlined by Brandt et al. (1996); however, we took the larger value of 7 GeV/c for the rigidity. We rebinned the spectral files so that each energy bin contained a minimum of 20 photons. We retained SIS data in the 0.5 to 10 keV range and GIS data in the 1 to 10 keV range. The background was measured from rectangular regions on the two edges of the chip farthest from the source (SIS data), or from annuli with inner radii > 6 arcmin (GIS data). These data were cleaned and filtered in the same manner as the source files.

Note that for the simultaneous ASCA/RXTE observations, we combined the two SIS detectors into a single spectrum, and we combined the two GIS detectors into a single spectrum, properly weighting the response matrices. We accounted for the cross-calibration uncertainties of the SIS and GIS instruments relative to each other and relative to RXTE by introducing a multiplicative constant for each detector in all of our fits. Note also that the phase filtering option in xselect produces flawed results, so the time filtering option was used instead to produce phase selected spectra.

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