THE NATURE OF THE HARD X-RAY–EMITTING SYMBIOTIC STAR RT CRU

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ABSTRACT

We describe Chandra High Energy Transmission Grating Spectrometer observations of RT Cru, the first of a new subclass of symbiotic stars that appear to contain white dwarfs (WDs) capable of producing hard X-ray emission out to greater than 50 keV. The production of such hard X-ray emission from the objects in this subclass (which also includes CD−57 3057, T CrB, and CH Cyg) challenges our understanding of accreting WDs. We find that the 0.3–8.0 keV X-ray spectrum of RT Cru emanates from an isobaric cooling flow, as in the optically thin accretion disk boundary layers of some dwarf novae. The parameters of the spectral fit confirm that the compact accretor is a WD, and they are consistent with the WD being massive. We detect rapid, stochastic variability from the X-ray emission below 4 keV. The combination of flickering variability and a cooling flow spectrum indicates that RT Cru is likely powered by accretion through a disk. Whereas the cataclysmic variable stars with the hardest X-ray emission are typically magnetic accretors with X-ray flux modulated at the WD spin period, we find that the X-ray emission from RT Cru is not pulsed. RT Cru therefore shows no evidence for magnetically channeled accretion, consistent with our interpretation that the Chandra spectrum arises from an accretion disk boundary layer.

Subject headings: accretion, accretion disks — binaries: general — white dwarfs — X-rays

1. INTRODUCTION

Symbiotic stars are interacting binaries in which a hot, compact star accretes from the wind of a red giant companion. Although a few symbiotics contain neutron star accretors (e.g., GX 1+4, 4U 1700+24, 4U 1954+31, and IGR J16194−2810; Davidsen et al. 1977; Masetti et al. 2002, 2007a, 2007b; Galloway et al. 2002), the accreting compact object is usually a white dwarf (WD). Typical binary separations are on the order of AU, with orbital periods on the order of a few hundred days to a few decades (Kenyon 1986; Belczyński et al. 2000). Symbiotics can thus be thought of as very large cousins of cataclysmic variables (CVs). The accretion rate onto the WD appears to be high enough in most symbiotic systems that accreted material is burned quasi-steadily in a shell on the WD surface, producing a high UV luminosity (Sokoloski et al. 2001; Orio et al. 2007). Although accretion disks are likely to exist around the WDs in some symbiotics (Livio 1997; Sokoloski & Kenyon 2003), there is little direct evidence for these disks. Finally, the red giant wind produces a dense nebula that surrounds the system.

Most symbiotic stars with detectable X-ray emission display soft or supersoft thermal X-ray spectra. As in the supersoft X-ray sources, the lowest energy X-rays could emanate directly from material burning quasi-steadily on the WD surface (Jordan et al. 1994; Orio et al. 2007). Based on a survey of symbiotics with ROSAT, Münzer et al. (1997) proposed that symbiotics be classified according to the hardness of their X-ray spectra. They labeled sources with supersoft spectra “α-types,” sources with the slightly harder spectra likely to arise from the collision of the red giant and WD winds “β-types,” and systems with the hardest spectra that might be indicative of neutron stars “γ-types.” Although more recent observations using the broader X-ray coverage and greater sensitivity of Chandra and XMM-Newton have shown that some symbiotics do not fit into the simple α/β/γ classification scheme (e.g., Z And and o Ceti; Sokoloski et al. 2006; Karovska et al. 2005), most still appear to produce primarily soft X-rays (E < 3 keV).

With the advent of the sensitive hard X-ray detectors on the Swift and INTEGRAL satellites, a new picture has emerged. Some symbiotic stars can produce X-ray emission out to greater than 50 keV. Such hard X-ray emission has so far been detected from four symbiotics thought to harbor WDs: RT Cru (Chernyakova et al. 2005; Bird et al. 2007), T CrB (Tueller et al. 2005b; G. J. M. Luna et al. 2008, in preparation), CH Cyg (Mukai et al. 2007), and CD−57 3057 (Masetti et al. 2006; Bird et al. 2007). Although the origin of this hard X-ray emission is not known, there are some underlying similarities between these hard X-ray–emitting symbiotics. Unlike most other symbiotic stars, they display a high incidence of optical flickering. They also tend to have low optical line strengths, indicating that they are often only “weakly” symbiotic. Both the visibility of the optical flickering (which in most symbiotics is overwhelmed by reprocessed shell-burning emission; Sokoloski 2003) and the weakness or low ionization state of the optical lines suggest that quasi-steady shell burning is not taking place in these objects, either because (1) the WD is more massive or (2) the accretion rate is lower than in other symbiotics. Hard X-ray emission might therefore be a proxy for high WD mass. In fact, at least one of the hard X-ray symbiotics, T CrB, is a recurrent nova and contains a high-mass WD (Hachisu & Kato 2001). Finally, jet production appears to be more common in flickering symbiotics, and one of the four hard X-ray symbiotics, CH Cyg, regularly produces jets (Taylor et al. 1986; Karovska et al. 1998; Crocker et al. 2001, 2002). Other WDs in hard X-ray symbiotics might also harbor jets.

Cieslinski et al. (1994) classified RT Cru as a symbiotic star based on its optical spectrum. They noted that the lack of strong high-ionization emission lines and the very weak forbidden emission...
lines make the optical spectrum similar to that of T CrB. They detected optical flickering in the $U$ band with a timescale of a few tens of minutes. Except for GX 1+4 (Jablonski et al. 1997; Chakrabarty & Roche 1997), none of the neutron star—containing symbiotic stars produce optical flickering (e.g., Sokoloski et al. 2001), which is common in CVs, or show Balmer or He ii emission lines (Masetti et al. 2007b). The presence of optical flickering and Balmer and He ii emission lines from RT Cru (Cieslinski et al. 1994) suggests that it therefore contains an accreting WD rather than a neutron star. Reddening estimates from optical spectra and infrared magnitudes (coupled with the assumption that the radius of the M5 III red giant is about 0.5 AU; van Belle et al. 1999) suggest that RT Cru is between 1.5 and 2 kpc away (J. Mikolajewska 2006, private communication).

In 2003 and 2004, the IBIS instrument on board INTEGRAL detected hard X-ray emission extending out to $\sim 100$ keV from the source IGR J12349–6434, which Chernyakova et al. (2005) found to have a 20–60 keV flux density of $\sim 3$ mcrab. Masetti et al. (2005) suggested an association between IGR J12349–6434 and RT Cru, which observations with the Swift satellite later confirmed (Tueller et al. 2005a). The long-term optical light curve from the AAVSO indicates that at the time of the INTEGRAL observations, RT Cru was in an optical bright state; it brightened from 13.5 to 11.5 mag sometime between 1998 and 2000. Between 2000 and 2005, the optical brightness slowly decreased to approximately 12.1 mag. The short (4.7 ks) Swift observation of 2005 August showed that between 2003 and 2005, the hard X-ray flux also decreased.

In this paper we describe Chandra High Energy Transmission Grating (HETG) observations of RT Cru, the first member of a new class of hard X-ray—emitting symbiotic WDs. We detail the observations and data reduction in § 2 and the results from spectral and timing analyses in § 3. In § 4 we discuss our interpretation of the observations, which confirm that the accreting compact object in RT Cru is a WD and provide some of the most direct evidence to date for an accretion disk around a wind-fed WD in a symbiotic system. In this section we also discuss the implications of a system that can accelerate particles to relativistic speeds and produce X-ray emission out to greater than 50 keV being powered by an accreting WD. We summarize our conclusions in § 5.

2. OBSERVATIONS AND DATA REDUCTION

On 2005 October 19, the Chandra X-ray Observatory performed a 50.1 ks Director’s Discretionary Time (DDT) observation of RT Cru using the HETG (Canizares et al. 2005) and the ACIS-S detector (ObsID 7186, start time 10:21:12 UT). We requested the DDT observation to attempt to catch RT Cru in the optical bright state that appeared to be associated with hard X-ray emission. We used the HETG instrument because the Swift XRT observation of 2005 August hinted at several possible emission-line complexes. The data were collected in timed exposure mode, in which the CCD chips were read out every 2.54 s. The data were time-averaged back to Earth in faint mode, which conveys photon arrival times, event amplitudes, and additional information for evaluating the validity of each event. We reduced the data according to standard procedures using the software package CIAO 3.3.

We extracted a spectrum from the undispersed light (the zeroth-order spot, which fell on the S3 back-illuminated chip) using a circular extraction region with a radius of 60" centered on the source coordinates: $\alpha = 12^h34^m43.74^s$ and $\delta = -64^\circ33'56.0''$. To obtain the background for the zeroth-order light, we extracted photons from a source-

FIG. 1.—Undispersed (zeroth-order) spectrum. The top panel shows the spectrum with the absorbed, isobaric cooling flow model overplotted. The bottom panel shows residuals with respect to this model (in units of $\chi^2$, where $\chi^2$ is shorthand for the difference between the data and the model, squared, divided by the variance, with the sign of the difference between the data and the model).

For the dispersed light from both of the HETG sets of gratings—the Medium Energy Grating (MEG) and the High Energy Grating (HEG)—we extracted spectra from each of the $m = \pm 1$, $\pm 2$, and $\pm 3$ orders individually (using the CIAO software tool dmtype2spin1t). To obtain the background for the dispersed light, we extracted counts from rectangular regions on either side of the spectral image. The count rate in the HEG and MEG $m = \pm 1$ orders was 0.042 and 0.034 counts s$^{-1}$, respectively. Although the dispersed spectral orders contained too few counts to produce a high signal-to-noise ratio spectrum of lines spanning the full energy range of the instrument, the combined $m = \pm 1$ spectrum (grouped at twice the full width at half-maximum of 0.012 Å) provided good-quality data in the region around the Fe K$_\alpha$ emission-line complex. We therefore used the zeroth-order spectrum for continuum fitting and the dispersed ($m = \pm 1$) spectrum primarily for analysis of the Fe lines. The HEG and MEG $m = \pm 2$ and $\pm 3$ spectra helped confirm the Fe line identifications. For spectral fitting of both the zeroth and higher order photons, we used the standard software packages XSPEC (Arnaud 1996) version 12.3.0 and ISIS (Houck 2002). The background contributed less than 1% of the total extracted dispersed and undispersed light.

We generated light curves in the energy bands 0.3–4.0 and 4.0–8.0 keV by extracting counts (with CIAO) from a region containing the zeroth-order spot and the $m = \pm 1$ dispersed orders of both the HEG and MEG. Since we estimated that there were only ~70 background counts in this extraction region during the course of the observation (compared to more than 9000 source counts), we did not background-subtract the light curves.

At high count rates, two or more photons can arrive close enough together in time that they appear to be a single event. This “pileup” phenomenon can cause a spectrum to become distorted and the count rate to be reduced. To confirm that the zeroth-order spectrum was not affected by pileup, we divided the number of counts at the peak of the point-spread function of the undispersed light by the number of 2.54 s frames in the observation to obtain an upper limit on the number of counts per pixel per frame. The resulting 0.08 counts per pixel per frame is well below the 1 count per pixel per frame where pileup can become important (Harris et al. 2004). Moreover, the average count rate in the zeroth order was significantly

1 Chandra Interactive Analysis of Observations (CIAO), available at http://cxc.harvard.edu/ciao/.
less than 1 count per frame time, indicating that the light curve was not significantly distorted by the saturation that can occur at higher count rates (i.e., higher pileup fractions). The pileup fraction in the higher order spectrum was negligible.

3. ANALYSIS AND RESULTS

3.1. Spectral Analysis

To model the X-ray spectrum, we first consider simple, single-component continuum models. We fit these models to the binned 0.3–8.0 keV zeroth-order spectrum (above 8.0 keV, the noise rises and the quantum efficiency drops sharply). Absorbed single-component emission models such as a thermal plasma, power law, or blackbody (plus Gaussian lines) do not produce acceptable fits. Even if we include complex absorption, such as an absorber that only partially covers the source, a power-law distribution of absorbers (as seen in some magnetic CVs; e.g., Done & Magdziarz 1998), or a “warm” ionized absorber, single-component emission models still do not produce acceptable fits.

Including an additional broadband emission component improves the fitting results. The spectrum is formally well fitted with a highly absorbed, optically thin thermal plasma (MEKAL model in XSPEC), plus a moderately absorbed nonthermal power-law component. Since there is some degeneracy between the amount of absorption and the power-law index, we determine the power-law component has an absorbing column of $n_{\text{H}} \approx 10^{22} \text{ cm}^{-2}$ and an absorbing column $n_{\text{H}}$ partial covering (10$^{22}$ cm$^{-2}$) is 65 (52, 78).

The fractional amplitude of the stochastic variations appears to be largest in the 0.3–8.0 keV energy range. In the 508 s time series, the ratio of measured fractional rms variability, to that expected from Poisson fluctuations alone, is 9.1 (7.5, 10.2). Since there is some degeneracy between the amount of absorption and the power-law index, we determine the power-law component is not sensitive to the value to which we fix $kT_{\text{exp}}$, $s_{\text{exp}}$ is 1.96 ($\sigma = 1.6$, 2.0). The fractional rms variation, to that expected from Poisson fluctuations alone, is 3.1 (2.4, 3.9).

4.0 keV time series, the ratio of measured fractional rms variability, to that expected from Poisson fluctuations alone, is 9.1 (7.5, 10.2). Since there is some degeneracy between the amount of absorption and the power-law index, we determine the power-law component is not sensitive to the value to which we fix $kT_{\text{exp}}$, $s_{\text{exp}}$ is 1.96 ($\sigma = 1.6$, 2.0). The fractional rms variation, to that expected from Poisson fluctuations alone, is 3.1 (2.4, 3.9).

Note.—The model consists of optically thin thermal emission from an isobaric cooling flow with absorbers that both fully cover and partially cover the source, plus a Gaussian line.

Using solar abundance of Anders & Grevesse (1989).

The best absorption model consists of both a photoelectric absorber that fully covers the source and another that only partially covers it. Table 1 lists the best-fit parameters for this model, which, as we discuss in §4, we believe provides the best description of the Chandra spectrum of RT Cru.

In the first-order spectrum, we detect the iron-line complex spanning roughly 6.4–7.0 keV. Figure 2 shows the region around the iron-line complex in the combined MEG and HEG first-order ($m = \pm 1$) spectrum. Because of the large absorption and the resulting low count rate at low energies, we are not sensitive to lines such as O viii ($\sim 19$ Å) and Ne x ($\sim 12$ Å) that have been seen in HETG observations of some other accreting WDs (e.g., Pandel et al. 2005; Mukai et al. 2003). For the Fe lines, we use a simple power law to establish a continuum level and two Gaussian profiles to fit the Fe Kα, H-like Fe, and He-like Fe lines. To avoid the possible introduction of errors from misalignment of the HEG and MEG spectra, we use only the combined HEG first-order ($m = \pm 1$) spectrum for computation of the equivalent widths (EWs). Table 2 lists the line-center energies and EWs. Although we do not have enough counts to use the recombination, intercombination, and forbidden components of the H- or He-like Fe lines as density diagnostics, the observed line strengths and EWs confirm that the source is surrounded by a large amount of neutral material and that the abundances might be slightly subsolar. The Fe Kα EW of 108 eV is consistent with that expected for a source inside a cloud of cold material with an $N_{\text{H}}$ of $\sim 10^{21} \text{ cm}^{-2}$ (Inoue 1985), as we found from the continuum fitting.

3.2. Timing Analysis

Examining time series binned at 508.208 and 4065.664 s (i.e., 200 and 1600 times the frame time, respectively), we detected significant aperiodic, flickering-type variations on timescales of minutes to hours in the 0.3–4.0 keV emission. Figure 3 shows the 508 s binned time series (light curves) in the energy ranges 0.3–4.0 and 4.0–8.0 keV. The fractional amplitude of the stochastic variations appears to be largest in the 0.3–4.0 keV energy range. In the 508 s binned 0.3–4.0 keV time series, the ratio of measured fractional rms variation, $s$, to that expected from Poisson fluctuations alone, $s_{\text{exp}}$, is 1.96 ($\sigma = 36.6\%$ and $s_{\text{exp}} = 18.7\%$). We detect the 0.3–4.0 keV variability with even greater statistical significance in

### Table 1

| Parameter                      | Value (Min, Max) a |
|--------------------------------|--------------------|
| $M$ ($10^{-9} M_\odot \text{ yr}^{-1}$) | 1.8 (1.6, 2.0)     |
| $kT_{\text{max}}$ (keV)            | 80 (56, ...)       |
| $n_{\text{H}}$: full covering  ($10^{22}$ cm$^{-2}$) | 8.2 (7.7, 8.8) |
| $n_{\text{H}}$: partial covering ($10^{22}$ cm$^{-2}$) | 65 (52, 78) |
| Covering fraction               | 0.74 (0.69, 0.79) |
| Abundance (with respect to solar) | 0.30 (0.02, 0.45) |
| $F_{\text{Kx}}$ ($10^{-13}$ ergs cm$^{-2}$ s$^{-1}$) | 9.1 (7.5, 10.2) |
| $L_{\text{Kx}}$ ($10^{38}$ ergs s$^{-1}$) | 3.1 (2.4, 3.9) |

Note.—The model consists of optically thin thermal emission from an isobaric cooling flow with absorbers that both fully cover and partially cover the source, plus a Gaussian line.

a 90% confidence upper and lower limits.

b Accretion rate onto the compact object.

c Using solar abundance of Anders & Grevesse (1989).

d $F_{\text{Kx}}$ is the absorbed 0.3–8.0 keV flux, and $L_{\text{Kx}}$ is the unabsorbed 0.3–8.0 keV luminosity ($d = 2$ kpc).
the 4065 s binned time series; the ratio $s/s_{\text{exp}}$ in this case is 3.35 ($s = 22.1\%$ and $s_{\text{exp}} = 6.6\%$). In the 4.0–8.0 keV energy range, the 508 s binned time series has $s/s_{\text{exp}} = 1.36$ ($s = 16.6\%$ and $s_{\text{exp}} = 12.2\%$), and the 4065 s binned time series has $s/s_{\text{exp}} = 1.42$ ($s = 6.1\%$ and $s_{\text{exp}} = 4.3\%$).

We do not detect any periodic flux modulations. We are theoretically sensitive to an oscillation with fractional amplitude

$$A \approx 2\left(C_{\text{tot}} \frac{\alpha}{\delta} / \varepsilon\right)^{-1/2} \left(\frac{1 - \delta}{1 - (1 - \varepsilon)^{1/n_{\text{freq}}}}\right)^{1/2},$$

$$= 0.08 \left(C_{\text{tot}} / 9400\right)^{-1/2} \left(\frac{\alpha}{0.77}\right)^{-1/2},$$

where $C_{\text{tot}}$ is the total number of counts in the observation (ignoring the small number of background counts, which have a negligible effect), $\delta$ and $\varepsilon$ are small numbers related to the chance that a noise power in the power spectrum will exceed the detection threshold (both taken to be 0.05), $n_{\text{freq}}$ is the number of frequencies searched ($n_{\text{freq}} = 1644$), and $\alpha$ has an average value of 0.77 and depends on the location of the signal frequency in the frequency bin (see, e.g., van der Klis 1989; Sokoloski 1999). We are therefore sensitive to oscillations with fractional amplitudes of $\pm 8\%$ in regions of the power spectrum dominated by white noise, which in this case consisted of frequencies greater than $\approx 1.4$ mHz. In this analysis, we binned the time series in 15 s bins (i.e., 6 times the frame time). We were therefore sensitive to oscillations with periods as short as 30 s and most sensitive to oscillations with periods between 30 s and 12 minutes.

### 4. DISCUSSION

#### 4.1. Interpretation of the Chandra Observations

To estimate the radius of the accreting compact object, we take the unabsorbed 0.3–8.0 keV X-ray luminosity, $L_X$, to be either approximately equal to or a rough lower limit to the emission from an accretion disk boundary layer (we justify the assumption that the Chandra X-ray emission emanates from a boundary layer in the paragraphs that follow). Comparing this luminosity with that expected from accretion, $(1/2) \left(\frac{G M M/R}{R^2} \right) \geq L_X$, the radius of the accreting compact object is

$$R \lesssim 3.2 \times 10^8 \text{ cm} \left(\frac{M}{1.3 M_\odot}\right) \left(\frac{\dot{M}}{1.8 \times 10^{-9} M_\odot \text{ yr}^{-1}}\right),$$

where $R$ and $M$ are the radius and mass of the accretor, respectively, and $\dot{M}$ is the rate of accretion through the boundary layer. The radius is that of a WD. The Chandra X-ray spectrum therefore confirms that the compact object is a WD.

To determine whether the Chandra-band X-ray emission is indeed from an accretion disk boundary layer, we consider the rapid variability. Rapid flickering typically emanates from an accretion region close to a compact object. Our detection of flickering therefore suggests that the X-ray emission detected from RT Cru by Chandra is powered by accretion. This accretion could proceed via a wind-fed accretion disk, magnetic accretion columns, or Bondi-Hoyle-type direct impact of the accreting material onto the WD. While the two-component (thermal plasma plus power law) model provides a formally acceptable fit to the data, it is difficult to construct an interpretation of this model that is consistent with the rapid flickering from accretion onto a WD. The isobaric cooling

#### TABLE 2

| Parameter                  | Fe XXV       | Fe XXVI      | Fe Kα        |
|----------------------------|--------------|--------------|--------------|
| Line center ($\text{keV}$) | 6.946$^{+0.011}_{-0.013}$ | 6.693$^{+0.013}_{-0.016}$ | 6.379$^{+0.020}_{-0.021}$ |
| EW ($\text{eV}$)           | 72           | 60           | 108          |

* Superscripts and subscripts represent 90% confidence upper and lower limits, respectively.

* Gaussian fit equivalent widths. EW uncertainties are on the order of 10%–15%. 

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Fig. 2.—Iron-line complex from the combined HEG and MEG first-order ($m = \pm 1$) spectrum. The best-fit model of a power law plus three Gaussian emission lines is overplotted. The bottom panel shows the residuals, in the same units as Fig. 1.

Fig. 3.—Chandra light curves for RT Cru, with a bin size of 508.28 s. The light curves include the undispersed light, as well as the counts from the HEG and MEG $m = \pm 1$ orders. The top and bottom panels show the flux as a function of time in the energy ranges 0.3–4.0 and 4.0–8.0 keV, respectively. The 0.3–4.0 keV emission is clearly variable on timescales of minutes to hours.

Consistent with the presence of flickering in the light curves, the power spectrum rises at frequencies below 1.4 mHz. At these low frequencies, the power spectrum has a power-law index (i.e., slope on a log-log plot) of about $-1$. This "1/f noise" at low frequencies reduces our sensitivity to oscillatory signals with periods greater than approximately 12 minutes. Since we expect the minimum oscillation amplitude to which we are sensitive to increase roughly as the square root of the rising average broadband power as we go to lower frequencies (i.e., longer periods), the oscillation amplitude required for detection increases gradually from $\approx 8\%$ to $\approx 15\%$ as we move from periods of 12 minutes to 1 hr. Taking into account the underlying broadband power, as well as the number of frequency bins searched, we did not detect any statistically significant oscillations in any portion of the power spectrum.
flow spectral model, on the other hand, (1) provides a good fit to
the data, (2) has been successfully applied to both the boundary
layer emission from nonmagnetic CVs (e.g., Mukai et al. 2003;
Pandel et al. 2005) and the accretion columns of magnetic CVs
(e.g., Cropper et al. 1998), and (3) provides a natural context for
the flickering from accretion.

Most CVs with X-ray emission as hard as that which INTEGRAL
and the Swift BAT have detected from RT Cru have magnetic fields
strong enough to channel the accretion flow into accretion col-
umns (B ∼ 10^5−10^6 G, where B is the magnetic field strength at
the WD surface). Of the eight CVs detected at energies greater
than ∼50 keV with the Swift BAT, all but SS Cyg are likely mag-
netic accretors (Barlow et al. 2006). In these systems, the hard
X-rays come from hot gas behind the standoff shock in the accre-
tion column. Magnetic CVs typically have X-ray oscillations with
pulsation amplitudes of tens of percent at the WD spin period,
which is usually less than an hour (Warner 1995). Since typical
symbiotic-star accretion rates are higher than typical CV accretion
rates, if the WD in RT Cru was strongly magnetic and in spin equi-
librium, the spin period would probably be either comparable to
or faster than those in CVs. Given our sensitivity to oscillations
with periods less than an hour, we therefore should have detected
a spin modulation if RT Cru was magnetic. In fact, the power
spectrum has no statistically significant peaks. We conclude that
RT Cru is probably not a magnetic accretor. We thus favor the pic-
ture in which the X-ray emission from RT Cru detected by Chandra
is from a cooling flow in an accretion disk boundary layer.

4.2. Implications

The parameters of the cooling flow fit to the boundary layer
emission provide the accretion rate, as well as information about
the WD. From the normalization parameter of the cooling flow
model, the accretion rate onto the WD is \dot{M} = 1.8 \times 10^{-9} M_\odot yr^{-1}
(d/2 kpc)^2 (see Table 1). Symbiotic stars have accretion rates that
are on average higher than those in CVs. The accretion rate we
have found for RT Cru is consistent with this picture. It is also,
however, just low enough that we expect the boundary layer to
remain optically thin; Narayan & Popham (1993) find that for a
1 M_\odot WD, the boundary layer remains optically thin for accretion
rates below 3 \times 10^{-9} M_\odot yr^{-1}.

The parameters of the cooling flow fit also indicate that the
WD radius is small, suggesting that the WD could be quite massive.
Taken at face value, the radius constraint would imply that the
WD mass is at least 1.3 M_\odot. The high upper cooling flow tem-
perature, kT_{\text{max}} ≥ 55 keV (see Table 1), supports the conclusion
that the accretor is a massive WD. The relationship between kT_{\text{max}}
and WD mass is due to the fact that the Kepler velocity (v_K =
GM/R) is greater in the deep potential well of a more massive WD.
Since the boundary layer material is shock heated, and the initial
postshock temperature (T_{\text{max}}) is proportional to velocity squared,
T_{\text{max}} increases with WD mass. Alternatively, if we equate the
amount of energy available per particle, (1/2)\mu m_p v_K^2, where \mu is
the mean molecular weight and m_p is the mass of a proton, with the
energy released per particle in an isobaric cooling flow, (5/2)kT_{\text{max}}
(Pandel et al. 2005), we see that kT_{\text{max}} \propto v_K^2 \propto GM/R. Although
the determination of kT_{\text{max}} from X-ray emission below 8 keV is
highly uncertain, we can still ask what such a high kT_{\text{max}} would
imply if it is confirmed by an instrument with greater high-energy
sensitivity (such as Suzaku). For their sample of nine nonmagneti-
c CVs, Pandel et al. (2005) found that the upper cooling flow
temperature was roughly consistent with the expected kT_{\text{max}} =
(3/5)kT_{\text{vir}}, where T_{\text{vir}} is the virial temperature [defined by
(3/2)kT_{\text{vir}} = (1/2)\mu m_p v_K^2]. Using the WD mass-radius relation-
ship of Hansen & Kawaler (1994) a maximum cooling flow tempera-
ture of \kT_{\text{max}} > 55 keV implies M ≥ 1.3 M_\odot.

The high absorbing columns for both the partially covering
and fully covering absorber, as well as the covering factor of >0.7
for the partially covering absorber (see Table 1), indicate that the
X-ray source is highly obscured at this epoch. Since the X-ray
emission region is small, the absorber that only partially covers
the X-ray source must also be small. A possible source of this partially
covering absorber is an accretion structure such as an accretion
disk seen almost edge-on (as in OY Car; Pandel et al. 2005). We
assume that the fully covering component of the absorption com-
prises both interstellar absorption (1.1 \times 10^{22} cm^{-2} from NASA/
IPAC IRSA) and intrinsic absorption. The column density of this
absorber is probably high because the WD orbits within the strong,
dense stellar wind from the red giant. RT Cru has an orbital period of
~450 days (J. Mikolajewska 2006, private communication), and
therefore a binary separation on the order of an AU. This separa-
tion puts the WD well within the dense region of the red giant
wind. Month timescale variations in the absorption (not correlated
with the orbital period) have been detected by Swift (J. Kennea
et al. 2008, in preparation), suggesting that either the red giant wind
is clumpy, that the mass-loss rate in the wind of the red giant is
variable, or the accretion structure or structures partially blocking
the WD boundary layer must be unstable.

4.3. The Nature of RT Cru

As shown by the INTEGRAL detection in 2003–2004
(Cernyakova et al. 2005), RT Cru can at times produce X-ray emis-
sion out to greater than 60 keV. From the broadband flux densi-
ties reported by Cernyakova et al. (2005), the hard X-ray spectrum in
2003–2004 appears consistent with a power law with photon
index \Gamma = 2.7 (energy index \alpha = 1.7), and the 16–100 keV lumino-
sity at that time was approximately 10 L_o (d/2 kpc)^2. By 2005,
however, the 16–100 keV luminosity had dropped, and the hard
X-ray spectrum was closer to thermal (J. Kennea et al. 2008, in
preparation). To better appreciate the properties of the unusual
accreting WD in RT Cru, we briefly explore the possible sources
of the power-law hard X-ray emission observed by INTEGRAL in
2003–2004. In particular, we consider direct synchrotron emission,
inverse Compton (IC) scattering from a thermal distribution of
electrons, and IC scattering from a nonthermal distribution of
electrons. IC scattering from a nonthermal distribution of electrons
turns out to be the most likely option.

One way to generate a power-law energy spectrum is with
synchrotron emission from an electron with Lorentz factor \gamma emitted
at a frequency \nu \gamma = \nu \gamma_{\text{sync}} (3 \sin \alpha/2 \gamma_{\text{sync}}^2 (qBm_e/c),
where \alpha is the pitch angle, q is the electron charge, B is the mag-
netic field strength, m_e is the electron mass, and \nu is the speed of
light (Rybicki & Lightman 1979, p. 179). Since we did not detect X-ray
pulsations from RT Cru, the magnetic field at the surface of the WD is
probably not strong enough to disrupt the accretion flow, and there-
fore less than ∼10^5 G. Thus, even near the surface of the WD,
Lorentz factors \gamma_{\text{sync}} of a few times 10^5–10^8 would be needed to
produce significant direct synchrotron emission at 60 keV. We can
estimate the maximum Lorentz factor to which electrons will be
accelerated by setting the diffusive shock acceleration timescale
equal to the synchrotron cooling timescale. Following the approach
of Markoff et al. (2001), we equate the synchrotron loss rate to a
conservative acceleration rate (see Jokipii 1987) to find a maxi-
mum Lorentz factor to which electrons can be accelerated of
\gamma_{\text{max}} ≈ 2700(B/10^4 G)^{-1/2}(\xi/100)^{-1/2}, where \xi is the ratio of the
diffusive scattering mean free path to the gyroradius. Thus, $\gamma_{\text{max}}$ is 1–2 orders of magnitude below $\gamma_{\text{synch}}$. Moreover, whereas significant power from a distribution of synchrotron-emitting relativistic electrons would also be expected at energies below 15 keV, the 16–100 keV X-ray luminosity of $\approx 10^3 L_\odot$ during 2003 and 2004 is already close to the total energy budget available from accretion. Finally, to generate the X-ray spectral index observed by INTEGRAL from direct synchrotron emission, one would need a distribution of electrons that is much steeper than expected from standard theories of particle acceleration in shocks (Ellison et al. 1990). It is therefore unlikely that the hard X-ray emission from RT Cru was due to direct synchrotron emission.

As an aside, we note that the production of significant synchrotron emission at radio wavelengths would not require such high Lorentz factors. The ratio of synchrotron power to IC power from an electron is equal to the ratio of the energy density in the magnetic field to the energy density in photons (Rybicki & Lightman 1979, p. 201). Examining this ratio as a function of distance from the WD, we expect a similar amount of power from direct synchrotron and IC scattering near the surface of the WD, where the B field could be strong ($B \sim 10^4$ G). We therefore suggest that the next time RT Cru is in a power-law hard X-ray state like the one detected by INTEGRAL in 2003–2004, radio observations be performed to look for radio synchrotron emission.

Hard X-rays can be produced with much lower Lorentz factors through IC scattering. For photons scattering off of a thermal distribution of electrons, Reynolds & Nowak (2003) give a relation between the observed photon index $\Gamma$ and the Compton $y$-parameter, which is related to the factor by which the average photon energy increases. A steep photon index of $\Gamma > 2$ indicates a $y$-parameter less than 1, in which case there is no significant upscattering. Therefore, since RT Cru had a steep photon index of $\Gamma \approx 2.7$, the scattering off of a thermal distribution of electrons could not have been responsible for the power-law hard X-ray emission. Nonthermal, relativistic electrons must have been involved in producing the power-law spectrum observed by INTEGRAL. RT Cru thus contains a WD that can accelerate electrons to relativistic speeds. Three other systems that contain WDs that also generate relativistic electrons are CH Cyg, RS Oph, and possibly R Aqr, all of which have jets (Rupen et al. 2007; O’Brien et al. 2006; Crocker et al. 2001; Nichols et al. 2007).

Assuming now that the power-law hard X-ray spectrum was due to IC scattering from a power-law distribution of relativistic electrons, we can estimate the location of the scattering electrons. Since the strength of a dipole $B$ field falls like $1/r^3$, whereas the energy density in the photon field only falls like $1/r^2$, IC scattering will dominate as one moves farther from the WD. If we ask how far away from the radiation source the IC region should be to give us an IC cooling time on the order of a year (the approximate duration of the power-law hard X-ray state), we find that it should be a few tenths of an AU away. Given the orbital period for this system, that could put the IC emission region either between the WD and the red giant, as in a colliding-winds region, above the WD disk in a corona, or at the base of a jet. A model consisting of IC scattering off of relativistic electrons in a corona or at the base of a jet reproduces the observed hard X-ray emission well in X-ray binaries (Markoff et al. 2005). RT Cru’s steep power-law index is similar to that seen in the steep power-law state in microquasars.

5. CONCLUSIONS

We have observed the first symbiotic star with X-ray emission out to greater than 60 keV with the HETG on Chandra. The stochastic variability and cooling flow–type spectrum suggest that RT Cru is powered by accretion onto a WD through a disk with an optically thin boundary layer. The accretion rate is near the top of the range for which the boundary layer can remain optically thin. The high initial temperature of the cooling flow and the high luminosity given the accretion rate from the spectral fit suggest that the WD in RT Cru could be quite massive. More generally speaking, it would be difficult to get such hard X-ray emission from accretion onto a low-mass WD with a shallow potential well and low Kepler velocity. Given the nature of the power-law hard X-ray emission previously observed by INTEGRAL, it therefore appears that the accreting, nonmagnetic WD in RT Cru is able to generate a nonthermal, power-law distribution of electrons and very hard X-ray emission through IC scattering. Three other systems in which WDs can accelerate electrons to relativistic speeds (RS Oph, CH Cyg, and possibly R Aqr; Rupen et al. 2007; O’Brien et al. 2006; Crocker et al. 2001; Nichols et al. 2007) all have jets. Radio observations of RT Cru during the next power-law hard X-ray state like that observed by INTEGRAL in 2003 and 2004 could play an important role in diagnosing this system and determining the extent to which some symbiotic stars might constitute the nanoquasar analog to microquasars (Zamanov & Marziani 2002).

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