SYMBIOTIC STARS IN X-RAYS. III. SUZAKU OBSERVATIONS

N. E. NUÑEZ1, T. NELSON2, K. MUKAI3,4, J. L. SOKOLOSKI5, and G. J. M. LUNA6

1 Instituto de Ciencias Astronómicas de la Tierra y del Espacio (ICATE-UNSJ, CONICET), Av. España (S) 1512, J3402DSP, San Juan, Argentina; nunez@icate-conicet.gov.ar
2 Minnesota Institute for Astrophysics, University of Minnesota, Minneapolis, MN, 55455, USA
3 CRESTT and X-ray Astrophysics Laboratory, (NASA/GSFC), Greenbelt, MD 20 771, USA
4 Department of Physics, University of Maryland, Baltimore County, 1000 Hilltop Circle, Baltimore, MD, 21 250, USA
5 Columbia Astrophysics Lab, 550 W120th St., 1027 Pupin Hall, MC 5247 Columbia University, 10027, New York, USA
6 Instituto de Astronomía y Física del Espacio (IAFE, CONICET-UBA), Av. Güiraldes 2620, C1428ZAA, Buenos Aires, Argentina

Received 2015 May 5; accepted 2016 April 15; published 2016 June 7

ABSTRACT

We describe the X-ray emission as observed by Suzaku from five symbiotic stars that we selected for deep Suzaku observations after their initial detection with ROSAT, ASCA, and Swift. We find that the X-ray spectra of all five sources can be adequately fit with absorbed optically thin thermal plasma models, with either single- or multi-temperature plasmas. These models are compatible with the X-ray emission originating in the boundary layer between an accretion disk and a white dwarf. The high plasma temperatures of $kT > 3$ keV for all five targets were greater than expected for colliding winds. Based on these high temperatures as well as previous measurements of UV variability and UV luminosity and the large amplitude of X-ray flickering in 4 Dra, we conclude that all five sources are accretion-powered through predominantly optically thick boundary layers. Our X-ray data allow us to observe a small optically thin portion of the emission from these boundary layers. Given the time between previous observations and these observations, we find that the intrinsic X-ray flux and the intervening absorbing column can vary by factors of three or more on a timescale of years. However, the location of the absorber and the relationship between changes in accretion rate and absorption are still elusive.

Key words: binaries: symbiotic – X-rays: individual (CD −28 3719, EG And, Hen 3-461, Hen 3-1591, 4 Dra)

1. INTRODUCTION

When observed at optical wavelengths, symbiotic stars (SS) show a composite spectrum that suggests that they are binary systems. A hot, compact component (usually a white dwarf, WD) contributes to the blue–UV region of the spectrum, while a cool red giant dominates the spectrum at longer wavelengths.

Observations at other wavelengths reveal a very complex and rich scenario for these systems. Optical, infrared, and UV spectral regions are rich in emission lines from forbidden and permitted transitions, which arise mainly from photoionization and recombination of the nebular plasma heated by the hot component (Kenyon 2009). Radio, optical, and X-ray observations reveal jets with velocities of a few hundred to around $1000$ km s$^{-1}$ (e.g., Crocker et al. 2001; Brockopp et al. 2004; Kellogg et al. 2007) and thermal emission from the ionized red giant wind (Seaqust & Taylor 1990; Seaqust et al. 1993). SS can even produce $\gamma$-rays during nova eruptions (e.g., V407 Cyg, Abdo et al. 2010; Ackermann et al. 2014). Symbiotics are now recognized as a population of X-ray sources. From the $\sim 220$ systems known (Belczyński et al. 2000), $45$ have been detected at X-ray wavelengths, most of them with emission in the $0.3−10$ keV range. A few, however, were detected at energies up to $100$ keV (Kennea et al. 2009).

The X-ray emission from SS consist of some combination of four distinct spectral components (dubbed $\alpha$, $\beta$, $\gamma$, and $\delta$), which most likely arise from distinct emission regions and/or processes (Luna et al. 2013, hereafter Paper I). In particular, $\alpha$-, $\beta$-, and $\delta$-type X-ray spectral components come from thermal X-ray emission (optically thin or blackbody-type) that arises from the quasi-stable nuclear burning on the WD surface ($\alpha$), a colliding-wind region with $kT \lesssim 1$ keV ($\beta$), or an accretion disk boundary layer ($\delta$). Those symbiotics with a neutron star as the accreting compact object and non-thermal, power-law-type X-ray spectra are classified as $\gamma$-type by Mürset et al. (1997).

Sensitive and broadband X-ray satellites such as Suzaku have played a significant role in observing symbiotics, especially those with X-ray emission above $10$ keV (T CrB, CH Cyg, V648 Car; Mukai et al. 2007; Luna et al. 2008; Kennea et al. 2009). Luna et al. (2013) and Nuñez et al. (2014) studied and classified the first X-ray detections of five symbiotics with Swift, XMM-Newton, and/or Chandra. Here we describe Suzaku observations of CD −28 3719, Hen 3-1591, Hen 3-461, EG And, and 4 Dra.

2. OBSERVATIONS AND DATA REDUCTION

Suzaku observed the five SS with the XIS (Koyama et al. 2007). Details of each observation are presented in Table 1. Data were taken with the XIS0, XIS1, and XIS3 detectors, which are sensitive in the $0.2−12$ keV range (XIS2 has not been operational since 2006 November). All sources were too faint to be detected with the Hard X-ray Detector. We reprocessed all data using the aepipeline script and obtained event files by applying processing version 2.5.16.29 (2014-07-01).

Source spectra and light curves were extracted from circular regions centered on the source SIMBAD6 coordinates.
Table 1
Observation Log

| Source     | Date       | ObsId     | Exp. Time (ks) |
|------------|------------|-----------|----------------|
| CD –28 3719 | 2013 Oct 12 | 408032010 | 14             |
| Hen 3-1591  | 2012 Oct 03 | 407042010 | 51             |
| –ASCIA      | 1999 Sep 22 | 57055000  | 15             |
| Hen 3-461   | 2012 Dec 17 | 407007010 | 46             |
| EG And      | 2011 Feb 05 | 405034010 | 100            |
| 4 Dra       | 2010 Apr 18 | 405035010 | 42             |
|            | 2011 Nov 09 | 406041010 | 42             |

The recommended radius of the extraction region \(^7\) is 260″ (this size encircles 99% of the point source flux); given the source and background brightnesses, however, we were able to use this size only in the case of 4 Dra. Comparing the source spectra with that of the background, we found that the optimal radius for the source region, which maximizes the signal-to-noise ratio, was of 120″ in the case of Hen 3-1591, CD -28 3719, and EG And, and 60″ for Hen 3-461. Background spectra and light curves were extracted from annular regions centered on the source (with inner and outer radii of 340″ and 430″, respectively) in the case of Hen 3-1591, CD -28 3719, Hen 3-461, and 4 Dra, while a circular region with a 160″ radius was used for EG And because the location of the source on the chip did not allow us to select an annular region for the background. The response matrices were created using the xisarfgen and xisarfgen tools. We then fit the binned spectra (grouped by a minimum of 20 to 25 counts per bin) using XSPEC\(^8\) and the \(\chi^2\) statistic to select the best-fit models.

One of our targets, Hen 3-1591, was observed serendipitously with ASCA (Tanaka et al. 1994) on 1999 September 22 during an observation of the supernova remnant (SNR) G5.2-2.6. The Solid-state Imaging Spectrometer (SIS) was operated in 1-CCD mode for this observation (of the four chips available), which put Hen 3-1591 outside the operational SIS field of view. However, Hen 3-1591 was securely in the field of view of the Gas Imaging Spectrometer (GIS) instrument, which has two units (GIS2 and GIS3). We selected intervals when the satellite was outside the South Atlantic Anomaly (SAA), when the attitude control was stable and the satellite pointed within 0°02 of the target, and when the line of sight was greater than 5° above the Earth limb. We also applied standard selection criteria, combining monitor count rates and geomagnetic cutoff rigidity to exclude time intervals of high-particle background, in the end obtaining 15 ks of good on-source data.

For the ASCA observation of Hen 3-1591, we extracted the source spectrum from a 6″ radius circular extraction region centered on the source and the background spectrum from a 6′ radius region centered at \(\alpha = 271.6619, \delta = -25.8192\), away from the SNR and other obvious sources. We used the v4.0 rmf downloaded from the CALDB and generated an arf file for each unit of the GIS. We then combined the GIS2 and GIS3 spectra and responses, ignored the data outside the well-calibrated range of 0.7–10 keV, and binned the data by a factor of 32, leaving 26 channels.

In those cases where the thermal nature of the emission was not obvious, i.e., lines arising from optically thin thermal emission were weak or absent, we evaluated whether any of three spectral models—an absorbed single-temperature optically thin thermal plasma, an absorbed multi-temperature cooling flow, or an absorbed non-thermal plasma—properly fit the data based on their \(\chi^2\). The parameters of the best-fit models are listed in Table 2. We used the Tbars model absorption that completely covered the sources of X-ray emission, using the abundances of Wilms et al. (2000) and the cross-sections of Verner & Yakovlev (1995).

Once the best model was found, we used the unbinned data and C-statistic (Cash 1979) to calculate the uncertainties in the parameters of the models and the flux. All errors in the fit parameters correspond to 90% confidence intervals (see Table 2).

3. RESULTS

3.1. Spectral Analysis

The X-ray emission from each of the five sources we observed with Suzaku was successfully modeled as absorbed, optically thin thermal emission from either a single- or multi-temperature plasma. Temperatures were high, with \(kT\) of about a few keV for all sources. The fluxes from both objects in common with Paper I (Hen 3-461 and CD -28 3719) were higher when observed with Swift than when observed more recently with Suzaku. The parameters from the best-fit models are listed in Table 2, while spectra are shown in Figure 1.

3.1.1. CD –28 3719

To improve the basic spectral modeling, we intended for our Suzaku observation to provide a spectrum with a higher signal-to-noise ratio than previous data sets. During the observation of CD –28 3719, however, there were some problems in the acquisition of the XIS0 chip data, which did not return to the 5 × 5 editing mode after dark frame dump during an SAA passage, and the data during these segments were corrupted. For this reason, we only analyzed the data from the XIS1 and XIS3 chips.

The presence of excess counts in the ~6.6 keV region led us to test optically thin thermal plasma models for the spectrum instead of non-thermal models, which should not produce emission lines in this spectral region. The Fe Kα fluorescent emission line, if present, should be centered at \(\approx 6.4\) keV. We interpret the line near 6.6 keV as being due to a combination of H-like, He-like, and fluorescent Fe lines. The best-fit model for this source, whose X-ray spectrum we show in Figure 1, consists of an absorbed, single-temperature, optically thin thermal plasma with variable abundance, Tbarsxspec. The metal abundance was 0.44\(^{+0.30}_{-0.17}\). The other best-fit model parameters are listed in Table 2. The results from this fit are commensurate with the results obtained from the Swift data analyzed in Paper I.

3.1.2. Hen 3-1591

Hen 3-1591 was serendipitously observed with ASCA/GIS, and our reduction of the ASCA data revealed that it was detected with a net count rate of 0.016 c/s/GIS. Figure 2 shows the ASCA spectrum of Hen 3-1591, which contains ~200 photons. A power-law fit with a photon index near 2.4, with excess counts around 6.6 keV, provides an acceptable fit. Adding a Gaussian, the line centroid was found to be near 6.6 keV with an equivalent width well in excess of 1 keV.

\(^7\) http://heasarc.gsfc.nasa.gov/docs/suzaku/analysis/abc/
\(^8\) http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/
| Object     | Model                                      | Count Rate (10^{-2} c s^{-1}) | $N_{H,22}$^{a} | $kT$^{b} (keV) | $F_X$^{c} | $L_X$^{d} | $\chi^2$/dof |
|------------|--------------------------------------------|--------------------------------|----------------|---------------|-----------|-----------|---------------|
| CD −28 3719 | $T_{babs} \times spec$                     | 0.9 ± 0.1                      | $10^{23}_{+14}^{−12}$ | 8.3 ± 1       | 14 ± 1    | 18 ± 1 (d/1 kpc)^2 | 1.2/181      |
|            | $T_{babs} \times mkflow$                   | …                              | $13_{-9}^{+12}$     | 11 ± 2        | 19 ± 1    | 22 ± 1 (d/1 kpc)^2 | 1.2/182      |
| Hen 3-1591 | $T_{babs} \times spec$                     | 3.7 ± 0.1                      | 0.04 ± 0.01       | 3 ± 1         | 6.0 ± 0.2 | 6.1 ± 0.2 (d/1 kpc)^2 | 1.2/210      |
|            | $T_{babs} \times mkflow$                   | …                              | 0.10 ± 0.04       | 6 ± 1         | 6.9 ± 0.3 | 7.8 ± 0.3 (d/1 kpc)^2 | 1.2/214      |
| Hen 3-461... | $apec+T_{babs} \times pcfabs \times (apec+Gauss)$ | 0.2 ± 0.1                      | $3_{-3}^{+5}$     | 8.3 ± 5       | 26 ± 5    | 31 ± 6 (d/1 kpc)^2  | 1.5/23       |
| EG And...... | $T_{babs} \times spec$                     | 0.4 ± 0.1                      | 0.3_{-0.2}^{+0.3}  | 3 ± 2         | 1.1 ± 0.2 | 0.4 ± 0.1 (d/512 pc)^2 | 0.9/134      |
|            | $T_{babs} \times mkflow$                   | …                              | 0.9 ± 0.3         | 3 ± 1         | 2.4 ± 0.2 | 0.8 ± 0.1 (d/512 pc)^2 | 1.1/134      |
| 1st scenario (see Section 3.1.5) | 4 Dra(4050) | $T_{babs} \times pcfabs \times vapec$ | 38 ± 1            | 0.43 ± 0.05  | 6.1 ± 0.2 | 118 ± 2 | 5 ± 1 (d/190 pc)^2    | 1.1/5406      |
|            | 4 Dra(4060) | $T_{babs} \times pcfabs \times vapec$ | 110 ± 1           | 0.96 ± 0.06  | 6.1 ± 0.2 | 577 ± 3 | 25 ± 2 (d/190 pc)^2   | 1.1/5406      |
|            | 4 Dra(4050) | $T_{babs} \times pcfabs \times mkflow$ | …                  | 0.47 ± 0.15  | 14 ± 1    | 130 ± 2 | 6 ± 1 (d/190 pc)^2    | 1.1/5406      |
|            | 4 Dra(4060) | $T_{babs} \times pcfabs \times mkflow$ | …                  | 1.32 ± 0.04  | 14 ± 1    | 640 ± 3 | 27 ± 1 (d/190 pc)^2   | 1.1/5406      |
| 2nd scenario (see Section 3.1.5) | 4 Dra(4050) | $T_{babs} \times pcfabs \times vapec$ | …                  | 0.47_{-0.03}^{+0.03} | 4.9 ± 0.3 | 124 ± 1 | 5 ± 1 (d/190 pc)^2    | 1.01/1794     |
|            | 4 Dra(4060) | $T_{babs} \times pcfabs \times vapec$ | …                  | 0.91 ± 0.07  | 6.4 ± 0.2 | 547 ± 2 | 24 ± 1 (d/190 pc)^2   | 1.05/3601     |
|            | 4 Dra(4050) | $T_{babs} \times pcfabs \times mkflow$ | …                  | 0.28_{-0.05}^{+0.30} | 7.3_{-0.8}^{+0.9} | 169 ± 2 | 7 ± 1 (d/190 pc)^2    | 1.01/1794     |
|            | 4 Dra(4060) | $T_{babs} \times pcfabs \times mkflow$ | …                  | 1.16 ± 0.08  | 3.1 ± 0.4 | 683 ± 2 | 30 ± 1 (d/190 pc)^2   | 1.05/3610     |

Notes.

^{a} Absorption column density (in units of 10^{22} atoms cm^{-2}) and covering fraction (CF) of the partial absorber model pcfabs.

^{b} Indicates the value of the maximum temperature in the case of the cooling flow model mkflow, kT_{max}, photon index of the model power law.

^{c} Unabsorbed X-ray flux, in units of 10^{-13} erg s^{-1} cm^{-2} in the 0.3–10.0 keV energy range.

^{d} Unabsorbed X-ray luminosity, in units of 10^{41} erg s^{-1} in the 0.3–10.0 keV energy range, scaled by the distances listed in Section 3.
(calculated by including eqwidth in the Gaussian component of the model). As this line is probably due to a combination of H-like, He-like, and fluorescent Fe lines, the X-ray emission should be modeled as optically thin thermal emission with reflection, adding the 6.6 keV line rather than a power law. In fact, a cooling flow plus Gaussian model gives a good description of the observed spectrum. The maximum temperature is around 14 keV, iron is strongly overabundant (∼twice the solar value), and the equivalent width of the fluorescent line (∼600 eV) also requires an overabundance of iron. This X-ray spectrum suggests that Hen 3-1591 hosts a WD accreting matter that is overabundant in Fe.

To model the Suzaku spectrum, we tested a non-thermal model like that suggested by the early ROSAT data (Mürset et al. 1997) and thermal models inspired by the ASCA data, which suggested that the X-ray emission is due to an optically thin thermal plasma. The two thermal models we tested (a single-temperature apec model and multi-temperature cooling

Figure 1. Suzaku/XIS spectra of (a) CD −28 3719, (b) Hen 3-1591, (c) Hen 3-461, (d) EG And, (e) 4 Dra ObsID 4050, and (f) 4 Dra ObsID 4060. The solid lines show the best-fit models described in Section 3. Red shows XIS1 data; black shows XIS0+3 data.
Almost two and half years after the Swift observation, Suzaku observed Hen 3-461 and only detected 285 source photons, i.e., an 8σ detection after background subtraction. Given the low number of photons detected, we were only able to perform crude spectral modeling ($\chi^2_r = 1.2$). We noticed that a weak soft component was detected at a low significance level (2σ). We thus decided to include a second component in our spectral model, being aware of the similarity with the well-known, two-spectral component $\beta$-type emission observed in a few WD symbiotics (e.g., NQ Gem, V347 Nor; see Paper I). We observed a strong excess of counts in the Fe Kα region, which is naturally explained if the emission originates in an optically thin thermal plasma. Thus, our best spectral model consisted of two optically thin thermal components and a Gaussian emission line at 6.4 keV to account for the fluorescent Fe Kα line. The hard component was modified by full and partial covering absorbers (apec+Tbabs*pcfabs $\times$ (apec+Gauss)).

3.1.3. Hen 3-461

Our Suzaku observation took place at orbital phase $\phi = 0.93$ (using the ephemeris from Kolb et al. 2004), with the WD moving behind the red giant wind (or $\phi = 0.17$ if we use the orbital period of 481 days and the ephemeris from Vogel 1991, i.e., the WD coming out of partial eclipse). After visual inspection of the Suzaku spectrum, we verified that no obvious features were present and grouped the channels to have a minimum of 20 counts per bin, which allowed us to use $\chi^2$ statistics to assess the quality of the fit. Several pieces of evidence suggest that the accreting compact object is a non-magnetic WD and thus that the X-ray spectrum could be modeled as due to optically thin thermal emission. To our knowledge, periodic modulations at the WD spin have not been detected in either optical or X-ray wavelengths, suggesting that synchrotron emission from a strong magnetic field is not present. In addition, Kolb et al. (2004) successfully model the UV emission with NLTE atmospheric models for a low-mass WD. We thus consider the best-fit model the one that consists of an absorbed, optically thin thermal plasma. The parameters are listed in Table 2.

3.1.4. EG And

We analyzed the two Suzaku observations, ObsIDs 405035010 and 406041010 (hereafter 4050 and 4060, respectively; see Table 1). Although in terms of $\chi^2_r$, an absorbed, non-thermal plasma plus a Gaussian emission line model (Tbabs $(\text{power+Gauss})$) fits the observed spectrum, the line centroid is at $\sim 6.67$ keV with an equivalent width of 0.17 keV, consistent with Fe xxv transitions from a thermal plasma. We thus prefer a thermal origin for the observed X-ray emission.

We obtained acceptable fits with spectral models of optically thin thermal plasma emission in two different scenarios. In the first scenario, we simultaneously fit both observations, linking the temperature of the optically thin thermal emission for both observations while allowing the absorption column to vary independently. This is a valid assumption if the X-ray-emitting plasma arises in the post-shock region of the accretion disk boundary layer and its temperature is set by the WD mass which does not change between observations. In the second scenario, we modeled both observations independently.

The first spectral model consists of an absorbed, single-temperature plasma with a reduced Fe abundance (vpec$^\alpha$). This model is formally acceptable for the two observations (see Table 2). However, in the case of 4060, there are significant residuals at energies below $\sim 1$ keV, suggesting that a simple absorption model is not completely appropriate. The fact that some flux is detected at energies below $\sim 1$ keV might be the footprint of an absorber that partially covers the X-ray source. We thus added such an absorber to our spectral model, significantly improving the fit for both observations. To quantify the fit improvement by the addition of a partial absorber, we performed 1000 simulations of both models following the LRT test, which shows that for 89% of the simulations, the fit improves with the extra, partial covering absorber (see Figure 3).

As an alternative, the second model consists of a multi-temperature cooling flow, again observed through both simple

\footnote{https://heasarc.gsfc.nasa.gov/xanadu/xspec/manual/XSmodelApec.html}
and partial covering absorbers. The X-ray spectrum was harder and the flux was higher for 4060 than for 4050. This is reflected in the higher $N_{H,22}$ (absorbing column in units of $10^{22}$ cm$^{-2}$) and covering fraction obtained using the first scenario, and the higher temperature obtained for the second scenario.

3.2. Timing Analysis

Significant stochastic variability of the X-ray flux on short (minutes to hours) timescales is a hallmark of accretion disks in binary systems. Periodic modulation, on the other hand, indicates that the accretion is channelled by a strong magnetic field (e.g., Z And, Sokoloski et al. 2006). We searched for periodic variations in the X-ray flux from our five targets, using light curves binned at 16 s and the Lomb-Scargle algorithm. No periods with a $p$ value $\leq 0.3$ were found for the sources in our sample. We used the ratio between the observed and expected rms variabilities ($s$ and $s_{\text{exp}}$, respectively) to quantify stochastic variations in the light curves. We binned the light curves at integer multiples of the XIS readout time: 16, 160, 1600, and 3680 seconds, and calculated the ratio $s/s_{\text{exp}}$ (see Table 3). Only 4 Dra showed significant variability, with amplitudes as high as 40%; the strongest flickering was present on timescales of minutes, consistent with previous determinations (Wheatley et al. 2003).

4. DISCUSSION

The X-ray emission in all five SS observed with Suzaku is consistent with a thermal origin, indicating the presence of shocked gas. We can use the derived temperature of this gas to infer the physical mechanism responsible for its production. In the case of X-rays from colliding winds ($\beta$-type emission), the post-shock temperature is related to the velocity difference between the two winds, fast and slow $((4/3) \times (v_{\text{fast}} - v_{\text{slow}}) = v_{\text{shock}})$, through the Rankine–Hugoniot strong shock conditions:

$$v_{\text{shock}} = (4/3) \times \frac{16kT_s}{3\mu m_H},$$

where $T_s$ is the post-shock temperature, $\mu$ is the mean molecular weight, and $m_H$ is the mass of a hydrogen atom.

Temperatures higher than $kT \sim 1$–2 keV are difficult to explain with this mechanism since there is little evidence of outflows with velocities $>1000$ km $s^{-1}$ in SS. If the emission instead originates in the accretion disk boundary layer (the assumed origin of $\delta$-type emission), then the temperature of the shocked gas is set by the gravitational potential of the WD and can be used to infer the mass of this. Assuming accretion through a disk, the velocity at the boundary layer is set by the inner Keplerian condition, and a lower limit on the mass can be calculated as follows:

$$M_{\text{WD}} \geq \frac{16T_s k R_{\text{WD}}}{3G\mu m_H},$$

where $G$ is the gravitational constant and $R_{\text{WD}}$ is the radius of the WD, calculated using the mass–radius relation of Pringle & Webbink (1975). The mass derived in this way should be considered only a lower limit because additional cooling mechanisms could be at play in the boundary layer region. One source of cooling that could be relevant for these systems is...
Compton cooling via UV photons from any optically thick portion of the boundary layer. This mechanism has been invoked in dwarf novae in outburst (Fertig et al. 2011) and in the recurrent nova RS Oph after its 2006 outburst (Nelson et al. 2011).

4.1. CD –28 3719

CD –28 3719 was detected in the X-rays for the first time in a short pointing observation with Swift, and in Paper I we classified its spectrum as δ-type. The Suzaku spectrum also shows the presence of hard, optically thin thermal X-ray emission observed through strong absorption, still compatible with a δ-type symbiotic. Using the plasma temperature from the cooling flow model to constrain the WD mass, we obtain $M_{\text{WD}} > 0.6 M_\odot$. CD –28 3719 seems to be the most stable source in our sample.

4.2. Hen 3-1591

Only two objects were classified by Mürset et al. (1997) as γ-type symbiotics based on their emission detected with ROSAT: GX 1+4 and Hen 3-1591. These observations had a limited signal-to-noise ratio, but Mürset et al. (1997) speculated that these sources harbored neutron stars as accretors. Recently, this type of symbiotic was named “symbiotic X-ray binaries” by Masetti et al. (2007).

Our best-fit model for Hen 3-1591, which consists of a thermal plasma rather than a power law, points to the presence of a WD as the accreting compact object instead of a neutron star, i.e., Hen 3-1591 is a WD symbiotic instead of a symbiotic X-ray binary as previously thought. Evidence supporting this scenario also comes from the optical spectrum, which shows many emission lines of a variety of ions, similar to that of a planetary nebula, where the strong UV radiation field from the WD photoionizes the surrounding nebula. Hedrick & Sokoloski (2004) detected flickering behavior in the B-band emission from this object, which suggests that the blue light is from an accretion disk. Hen 3-1591 belongs to a rare subclass of δ-type yellow symbiotics with a dusty IR continuum and located in the Galactic disk, so low metallicity is not implicated. They are interpreted as systems in which the hot component has recently evolved from the AGB to the WD stage. In this interpretation, the dust is from the mass lost by the AGB star, and the nebulosity is in fact the planetary nebula (PN), and neither is due to the present-day giant (see Jorissen et al. 2005 and references therein). In some ways this symbiotic system could therefore be comparable to the well-known classical novae GK Per (Bode et al. 1987) and V458 Vul (Wesson et al. 2008), both of which have been claimed to be classical novae inside PNe. These systems are all quite special if the PNe phase is as short as thought (10–20 kyr; Badenes et al. 2015).

Hen 3-1591 also shows barium syndrome, i.e., over-abundances of s-process elements and the presence of singly ionized barium, which cannot be explained unless the red giant is part of a binary system (Jorissen & Mayor 1992; Jorissen et al. 2005). The now-observed red giant had its photosphere polluted by s-process elements by the previously AGB companion, which now should be a WD. Thus, our high signal-to-noise, broadband Suzaku spectrum adds more support to the presence of a WD or hot subdwarf in Hen 3-1591. If we use the maximum plasma temperature from the cooling flow model to constrain the WD mass, we obtain $M_{\text{WD}} > 0.45 M_\odot$.

The high temperature of the plasma strongly suggests that in Hen 3-1591 the X-ray emission arises in an accretion disk boundary layer instead of a colliding-wind region. The strong shock condition implies wind speeds of around 3000 km s$^{-1}$ for the observed temperatures, and such high-speed outflows or winds have not been detected in Hen 3-1591 or almost any other symbiotic. The lack of UV data does not allow us to use the ratio of UV and X-ray fluxes as a proxy for the optical depth of the boundary layer. The decrease in temperature and luminosity between the ASCA and Suzaku observations, however, suggests that the optical depth of the X-ray-emitting plasma changed, being higher during the Suzaku observation. Suzaku might thus have observed a smaller optically thin portion of the boundary layer.

4.3. Hen 3-461

Hen 3-461 was discovered in X-rays with Swift during a short pointing observation (Paper I). The high temperature and absorption obtained from modeling those data, the hardness ratio (defined as the ratio of count rates in the 2.4–10/0.3–10 keV ranges), and the presence of significant flickering in the UV all suggested that the X-ray emission originated in the boundary layer of the accretion disk and led us to classify it as a δ-type source.

Our Suzaku observation indicates two important changes since the Swift observation: increased absorption toward the hard X-rays from the boundary layer, and the appearance of a new, softer δ-type component below 2 keV. Thus, the source shows us a β/δ-type spectra.

The intrinsic X-ray luminosity decreased by about 30% between the Swift observation in 2010 and the Suzaku observation in 2012 December. Although no contemporaneous UV data are available, GALEX (NUV) observations taken one year before our Suzaku observation indicate that $F_{\text{UV}} = 1.86 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, so that $F_{\text{UV}}/F_X \gtrsim 0.7$ (we quote a lower limit as the reddening for this source is unknown). Thus the accretion disk boundary layer still seems to be in the optically thin regime. In Paper I we proposed a scenario in which the soft emission of β/δ-type objects could be related to a colliding-wind region or jets. We could be witnessing the injection of new flows into a colliding-wind region. The equivalent width of the (unresolved) Fe Kα region of around 400 eV resembles the values found by Mukai et al. (2007) on the well-known jet source with a two-component X-ray spectra, CH Cyg.

4.4. EG And

In the V band, EG And is one of the brightest symbiotic systems. Its distance is 512 ± 168 pc (van Leeuwen 2007). The periodic photometric modulation indicates an orbital period of 470 days with an inclination of 82$^{+8}_{-4}$ degrees (Kolb et al. 2004), making EG And an eclipsing symbiotic binary.

Based on the high temperature ($kT = 3$ keV) found for the X-ray-emitting plasma (see Table 2), we can estimate a $M_{\text{WD}} \approx 0.4 M_\odot$ and rule out colliding winds as the source of X-rays in EG And. This source was identified as a δ-type symbiotic by Mürset et al. (1997). Those authors derived a temperature for the X-ray-emitting plasma of $kT = 1.3 \pm 0.5$ keV using ROSAT PSPC data—much lower than the temperature from our model of the Suzaku spectrum. The difference is most likely due to the
lack of sensitivity above 2 keV of the ROSAT spectrum. The velocity implied by the best fit to the Suzaku spectrum is \(\sim 1200 \text{ km s}^{-1}\), which is significantly faster than the highest velocity line features (\(\sim 700 \text{ km s}^{-1}\), C IV 1548, 1550 Å absorption features) found in UV spectra from FUSE and STIS by Crowley et al. (2008), and difficult to explain with outflows from a low-mass WD like the one in EG And by M_{WD} \approx 0.4 M_\odot (Kolb et al. 2004).

If the hot-component luminosities reported in the literature (16–400 L_\odot; Vogel et al. 1992; Kolb et al. 2004) are due to an accretion-powered WD, then the implied accretion rates are in the range \(10^{-8}–10^{-7} M_\odot \text{ yr}^{-1}\) for a 0.4 M_\odot WD. This is squarely in the regime where the boundary layer is expected to be optically thick according to models by Pophan & Narayan (1995). The X-ray luminosity is orders of magnitude lower than \(L_{\text{heat}}\) suggesting that the X-rays are produced in a region that remains optically thin at the outer surface of the mostly optically thick boundary layer. Although we expect X-ray emission due to accretion to be highly variable, EG And is very faint, and we do not detect enough photons to be sensitive to low-level variability (\(\sigma_{\text{exp}}/\langle \text{countrate} \rangle \sim 50\%\)).

4.5. 4 Dra

Although Reimers (1985) classified 4 Dra as a triple system consisting of 4 Dra(A) + CQ Dra(Ba)b, X-ray data obtained with ROSAT led Wheatley et al. (2003) to suggest that the X-ray emission is consistent with the presence of a WD accreting from the wind of a red giant. IUE data led Skopal (2005) to the same conclusion after fitting the SED. More evidence against the triple-system nature of 4 Dra comes from the analysis of the broad wings superimposed upon narrow emission lines in FUSE spectra by Froning et al. (2012), who found the FUSE spectra to be similar to other FUSE spectra of confirmed SS. Based on the previous studies and current results, when modeling the Suzaku spectra, we considered this source to be a symbiotic system with an accreting WD.

This source is one of the two systems with Hipparcos distances in our sample, having \(d = 190 \pm 17\) pc (van Leeuwen 2007). Its optical brightness presents irregular variations of about 0.1 mag in V (Eggen 1967), and radio flux variations also occur on timescales of weeks to months and may be shorter than hours to days (Brown 1987).

Our Suzaku observations of 4 Dra shows strong variability, a high \(kT\), and X-ray luminosities in the range of 0.01 L_\odot. If considered along with previous UV luminosities estimates of \(L_{\text{UV}} \approx 10 L_\odot\) by Skopal (2005), our findings suggest that 4 Dra is an accretion-powered symbiotic (i.e., no quasi-steady shell burning on the surface of the WD) in which mass is transferred at \(\sim 10^{-9} M_\odot \text{ yr}^{-1}\).

In such a case, the bulk of the boundary layer luminosity is emitted in the soft X-rays or EUV and is unobservable at Earth, while the remaining optically thin part of the boundary layer emits faint hard X-rays (Patterson & Raymond 1985). Our inference that the boundary layer is optically thick enables us to estimate the mass of the WD. Pophan & Narayan (1995) suggest that the accretion rates needed to produce a predominantly optically thick boundary layer around WDs of masses 1.0, 0.8, and 0.6 M_\odot are greater than \(10^{-7}\), a few times \(10^{-8}\), and \(\sim 10^{-8} M_\odot \text{ yr}^{-1}\), respectively. Taking the UV flux at the time of the Suzaku observation to be comparable to the \(\sim 10 L_\odot\) detected by IUE, the BL being optically thick suggests that the WD mass is less than about 0.6 M_\odot (the IUE luminosity corresponds to an accretion rate of \(\sim 10^{-8} M_\odot \text{ yr}^{-1}\)).

We emphasize that our conclusions about the optical depth of the accretion disk boundary layer and its implications for the WD mass depend on the assumed viscosity parameter, \(\alpha\), and other assumptions used in the models described by Pophan & Narayan (1995). As noted in Paper I, a 30% change in \(\alpha\) leads to a factor of a few change in the threshold accretion rate above which the boundary layer is expected to become optically thick. Allowing for this, the WD in 4 Dra probably has a mass less than about 0.7 M_\odot, still a low-mass WD.

Both fitting approaches discussed in Section 3.1.5 yield equally possible scenarios for 4 Dra. In the case where both spectra are modeled independently, the measured temperatures could be different because the optical depth of the emitting region changed, i.e., during the earliest observation the boundary layer was more optically thick and the measured temperature and fluxes of the X-ray-emitting plasma were lower. On the other hand, if we assume that during both observations the plasma temperature was the same (the optical depth of the boundary layer did not change between observations), we still obtain acceptable fits with an increase in the amount of absorbing material and intrinsic X-ray luminosity between the two observations, perhaps due to an increase in the accretion rate.

From the values of the absorbing column listed in Table 2, we conclude that the absorbing material is located relatively near the WD. The orbital solution for 4 Dra was studied by Famaey (2009, who used the radial velocities of the M giant to find a 1703 \pm 3 days period, an eccentric orbit (\(e = 0.3\), and \(T_0[\text{MJD}] = 53.204 \pm 19\). The ROSAT observations thus occurred at orbital phases \(\phi = 0.33, 0.15, \text{ and 0.61, while Suzaku observed at } \phi_{4050} = 0.23 \text{ and } \phi_{4060} = 0.57\). If the X-ray-absorbing material is tied to the orbital motion of the WD, the absorbing columns obtained from the fits of the Suzaku observations should not be very different given that during ObsID 4050 the system was near quadrature, while during ObsID 4060 the WD was in inferior conjunction. In that picture, the second observation (4060) taken during the inferior conjunction should be somewhat less absorbed, which is not the case. It is therefore probably intimately connected with the physics of accretion rather than to the orbit and the red giant companion.

5. CONCLUSIONS

We analyzed the deep, broadband Suzaku observations of five SS previously known to be X-ray sources. In contrast to observations obtained with ROSAT, which had limited energy coverage, or those obtained with Swift, which had limited continuous observing time, the spectra obtained with Suzaku allowed us to better unveil the origin of the X-ray emission in symbiotics. The high temperatures of the plasma of a few keV (see Table 2) imply shock speeds of more than a thousand km s\(^{-1}\) (assuming strong shock conditions). Given that such high-speed outflows are not typically observed in SS, this finding strongly suggest that the emission originates in an accretion disk boundary layer rather than a colliding-wind region.

The high temperatures are roughly consistent with shock-heated gas at the virial temperature in the deepest portion of the WD potential well, suggesting that Compton cooling of the
plasma in the boundary layer is not an important source of cooling.

As discussed in Paper I, Compton cooling of the post-shock region could be important if there is a source of abundant UV photons, high local accretion rate, and a relatively massive WD. The low UV luminosities from the sources presented here indicate that shell burning on the WD surface is not important, and thus the conditions for prevalent Compton cooling are not satisfied.

In Paper I, we proposed a new classification system for the X-ray emission from SS, in which the category δ was assigned to those sources with a high absorbing column (~a few $10^{22}$ cm$^{-2}$) and thermal X-ray emission with energies above 2.4 keV. The fraction of X-ray emission radiated in this hard regime (see Figure 4 in Paper I) may vary between different observations of the same source.

We calculated the hardness ratios (HR) as defined in Paper I using the Suzaku data or folding our best-fit models through the Swift/XRT responses. In both cases, we found that, except for CD $-$28 3719, all sources observed with Suzaku have HR $< 1$. In fact, for Hen 3-461 and CD $-$28 3719, the HRs changed dramatically between the first observations with Swift and the observations with Suzaku. Figure 4 in Paper I showed that during the Swift observations, all δ-type sources had HR $> 1$. The fact that we observed most sources to have HR $< 1$ indicates that while the δ components in the Luna et al. (2013) sample were all heavily absorbed, this is not universally true of all δ components; in this study, Hen 3-1591, EG And, and 4 Dra were all lightly absorbed and detected below 1 keV.

When compared with earlier data, all sources show changes in their intrinsic X-ray flux and $N_H$. Taking δ-type X-ray emission to originate in the accretion disk boundary layer, long-term changes in the X-ray flux are mostly related to changes in the accretion rate onto the WD, while changes in the soft X-rays can also be caused by variations in the amount of absorbing material.

The days-to-week timescale changes in $N_H$ observed in the δ-type prototype RT Cru (Luna & Sokoloski 2007; Luna et al. 2010) suggest that the absorber in that system is located close to the WD. However, it is unclear if these changes are related to the amount of material flowing through the accretion disk, and if so, how. In this study, we witness that although high flux states have high $N_H$ in the cases of CD $-$28 3719 and 4 Dra, in the case of Hen 3-461, $N_H$ is higher now, while $F_X$ is lower than when it was observed with Swift (see Table 2 in Paper I).

Of the five sources observed with Suzaku, CD $-$28 3719 retains its previous classification as a δ-type source (see Paper I), as derived from Swift observations. The proposed WD nature of the compact object in Hen 3-1591 and the temperature of the X-ray-emitting plasma suggest that it should now be considered a δ-type source instead of a γ-type source (those symbiotics with neutron stars as compact objects; see Mürset et al. 1997). The likely presence of a new soft component in the X-ray spectrum of Hen 3-461 encourages us to propose a β-δ-type classification for that object. No X-ray spectral type has previously been proposed for 4 Dra, and given the results obtained from our spectral fit, we advocate for a δ-type categorization. Finally, the low X-ray temperature derived for EG And, which is consistent with the low-mass estimate based on spectroscopy by Kolb et al. (2004) within the uncertainties on $kT$ and the broadband energy coverage, now shows that EG And should be considered a δ-type instead of a β-type source as originally proposed by Mürset et al. (1997).

N.E.N. acknowledges Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina (CONICET) for the Post-doctoral Fellowship. G.J.M.L. and N.E.N. acknowledge funding from PIP D-4598/2012, ANPCYT-PICT 0478/14, and Cooperación Internacional #D2771 from Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina. K.M. acknowledges support by NASA through ADAPT grant NNX13AJ13G. L.S. acknowledges support by NASA through ADAPT grant NNX15AF19G. This research has made use of data obtained from the Suzaku satellite, a collaborative mission between the space agencies of Japan (JAXA) and the USA (NASA) and the VizieR catalog access tool, CDS, Strasbourg, France. The original description of the VizieR service was published in Ochsenbein et al. (2000).

Facility: Suzaku.

REFERENCES

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010, *Sci*, 329, 817
Ackermann, M., Ajello, M., Albert, A., et al. 2014, *Sci*, 345, 554
Badenes, C., Maoz, D., & Ciardullo, R. 2015, arXiv:1502.01015
Belczyński, K., Mikolajewska, J., Munari, U., Ivison, R. J., & Friedjung, M. 2000, *A&A*, 146, 407
Bode, M. F., Roberts, J. A., Whittet, D. C. B., Sequist, E. R., & Frail, D. A. 1987, *Natur*, 329, 519
Brockopp, C., Sokoloski, J. L., Kaiser, C., et al. 2004, *MNRAS*, 347, 430
Brown, A. 1987, *ApJL*, 312, L51
Cash, W. 1979, *ApJ*, 228, 939
Crockett, M. M., Davis, R. J., Eyres, S. P. S., et al. 2001, *MNRAS*, 326, 781
Crowley, C., Espey, B. R., & McCandless, S. R. 2008, *ApJ*, 675, 711
Eggen, O. J. 1967, *ApJS*, 14, 307
Famaey, B. 2009, *A&A*, 498, 627
Fertig, D., Mukai, K., Nelson, T., & Cannizzo, J. K. 2011, *PASP*, 123, 1054
Froning, C. S., Long, K. S., Gänsicke, B., et al. 2012, *ApJS*, 199, 7
Hedrick, C., & Sokoloski, J. 2004, *BAAS*, 36, 1525
Jorissen, A., & Mayor, M. 1992, in *IAUS 151, Evolutionary Processes in Interacting Binary Stars*, ed. Y. Kondo, R. Sistero, & R. S. Polidan, 407
Jorissen, A., Zacs, L., Udry, S., Lindgren, H., & Musaeus, F. A. 2005, *A&A*, 441, i135
Kellogg, E., Anderson, C., Korreck, K., et al. 2007, *ApJ*, 664, 1079
Kennea, J., Mukai, K., Sokoloski, J. L., et al. 2009, *ApJ*, 701, 1992
Koleniuk, S. J. 2009, *The Symbiotic Stars (1st ed.): Cambridge: Cambridge University Press*
Kolb, K., Miller, J., Sion, E. M., & Mikolajewska, J. 2004, *AJ*, 128, 1790
Koyama, K., Tsunemi, H., Dotani, T., et al. 2007, *PASJ*, 59, 23
Luna, G. J. M., Sokoloski, J., & Mukai, K. 2008, in ASP Conf. Ser. 401, *RS Ophiuchi* (2006) and the Recurrent Nova Phenomenon, ed. A. Evans et al. (San Francisco, CA: ASP), 342
Luna, G. J. M., Sokoloski, J., Mukai, K., & Nelson, T. 2010, *ATel*, 3053 www.astronomerstelegram.org/?read=3053
Luna, G. J. M., & Sokoloski, J. L. 2007, *ApJ*, 671, 741
Luna, G. J. M., Sokoloski, J. L., Mukai, K., & Nelson, T. 2013, *A&A*, 559, 6
Masetti, N., Rigon, E., Maiorano, E., et al. 2007, *A&A*, 464, 277
Mukai, K., Ishida, M., Kilbourne, C., et al. 2007, *PASJ*, 59, 177
Müerset, U., Wolf, B., & Jordan, S. 1997, *A&A*, 319, 201
Nelson, T., Mukai, K., Orio, M., Luna, G. J. M., & Sokoloski, J. L. 2011, *ApJ*, 737, 7
Nuñez, N. E., Luna, G. J. M., Pillitteri, I., & Mukai, K. 2014, *A&A*, 565, A82
Ochsenbein, F., Bauer, P., & Marcout, J. 2000, *A&ASS*, 143, 23
Patterson, J., & Raymond, J. C. 1985, *ApJ*, 292, 550
Popham, R., & Narayan, R. 1995, *ApJ*, 442, 337
Pringle, J. E., & Webbink, R. F. 1975, *MNRAS*, 172, 493
Protassov, R., van Dyk, D. A., Connors, A., et al. 2002, *ApJ*, 571, 545
Reimers, D. 1985, *A&A*, 142L, 16
Sequist, E. R., Krogulec, M., & Taylor, A. R. 1993, *ApJ*, 410, 260
Sequist, E. R., & Taylor, A. R. 1990, *ApJ*, 349, 313
Skopal, A. 2005, *A&A*, 440, 958
Sokoloski, J. L., Kenyon, S. J., Espey, B. R., et al. 2006, *ApJ*, 636, 1002
Tanaka, Y., Inoue, H., & Holt, S. S. 1994, PASJ, 46, L37
van Leuween, F. 2007, A&A, 474, 653
Verner, D. A., & Yakovlev, D. G. 1995, A&AS, 109, 125
Vogel, M. 1991, A&A, 249, 173
Vogel, M., Nussbaumer, H., & Monier, R. 1992, A&A, 260, 156
Wesson, R., Barlow, M. J., Corradi, R. L. M., et al. 2008, ApJL, 688, L21
Wheatley, P. J., Mukai, K., & de Martino, D. 2003, MNRAS, 346, 855
Wilms, J., Allen, A., & McCray, R. 2000, ApJ, 542, 914