SUZAKU OBSERVATIONS OF FOUR HEAVILY ABSORBED HMXBs

D. C. Morris1, 2, R. K. Smith2, 3, C. B. Markwardt4, 5, R. F. Mushotzky2, J. Tueller2, T. R. Kallman2, and K. S. Dhuga1

1 Center for Nuclear Studies, Department of Physics, The George Washington University, Washington, DC 20052, USA; david.c.morris@nasa.gov
2 NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
3 Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, MD 21218, USA
4 CRESST and Astroparticle Physics Laboratory, NASA/GSFC, Greenbelt, MD 20771, USA
5 Department of Astronomy, University of Maryland, College Park, MD 20742, USA

ABSTRACT

We report on Suzaku observations of four unidentified sources from the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) and Swift-Burst Array Telescope Galactic plane surveys. All the sources have a large neutral hydrogen column density and show properties consistent with being supergiant X-ray binaries or supergiant fast X-ray transients (SFXTs), adding to the growing list of heavily absorbed XBs discovered by INTEGRAL. Two of the sources in our sample are approximately constant flux sources, one source shows periodic variation and one source exhibits a short, bright X-ray outburst. The periodicity is transient, suggesting it is produced by a neutron star in an elliptical orbit passing through a stellar wind, possibly one which is significantly clumpy. We analyze the flaring source in several segments to look for spectral variation and discuss the implications of the findings for the nature of the source. We conclude that all four sources in our sample can be identified as highly absorbed high mass X-ray binaries. This confirms the previous identification of IGR16195–4945 and IGR16465–4507 as such and reports new identifications in the cases of IGR16493–4348 and SWJ2000.6+3210. We report SWJ2000.6+3210 as a newly identified transient X-ray pulsar and confirm previous reports of SFXT flaring behavior in IGR16195–4945.

Key words: stars: neutron – X-rays: binaries

Online-only material: color figures

1. INTRODUCTION

With its first observation, International Gamma-Ray Astrophysics Laboratory (INTEGRAL; Winkler et al. 2003) began to uncover parts of the high mass X-ray binary (HMXB) population which had previously been largely unseen. Two specific HMXB subgroups whose numbers have been greatly increased by INTEGRAL observations are the highly absorbed sources (IGR16318–4848 being often cited as the archetype, Filliatre & Chaty 2004; Walter et al. 2003; Matt & Guainazzi 2003) and the supergiant fast X-ray transients (SFXTs; IGR17544–2619 being cited as the archetype, Pellizza et al. 2006). These sources have received extensive recent attention as an important component of the XB population, potentially detectable sources of gravitational radiation and gamma-ray burst progenitors (see, e.g., Chaty et al. 2008; Tomlick et al. 2008; Walter et al. 2006). The defining characteristic of the former subclass is high neutral hydrogen column density, >1023 cm−2 and of the latter is bright X-ray outbursts lasting several thousand seconds. Some sources from both subclasses are seen to exhibit relatively slow periodic variability (P ~ 1000 s). Since the initial identification of these subclasses, the INTEGRAL Galactic plane survey has discovered several more similar sources, suggesting that these objects, indeed, form previously undetected subclasses of X-ray binaries. Since the first INTEGRAL catalog (Bird et al. 2004) noted 28 unidentified sources from the INTEGRAL Galactic plane survey, many such sources have been followed up at X-ray and optical wavelengths and have been shown to belong to one or the other of these subclasses.

Nearly simultaneously to the discovery of these new subclasses by INTEGRAL, the Swift-Burst Array Telescope (BAT) Galactic plane survey began to uncover many new sources from its own survey. It was speculated, due to their absence from previous soft X-ray surveys, that some of these sources may be highly absorbed binaries, possibly members of the new subclasses seen in the INTEGRAL survey.

Several objects identified in the first INTEGRAL catalog, as of Fall 2006, remained without significant follow-up in the X-ray or at other wavelengths. During the Suzaku cycle 1 call for proposals, we proposed to follow-up three INTEGRAL detected sources that were suspected to be members of the new subclasses but had yet to be studied in detail. We proposed, furthermore, to observe two newly identified sources from the BAT Galactic plane survey to determine whether they were also members of either of these new HMXB subclasses.

In this paper, we detail the analysis of the Suzaku data collected on these sources, discuss the likelihood that these sources are similar to the originally discovered IGR sources and briefly discuss the possible nature of the new subclasses. This paper is organized as follows: in Section 2, we describe the observations and data analysis; in Section 3, we present our results; in Section 4, we discuss the similarity of each source and the propriety of associating them with one of these new subclasses and discuss the potential nature of these sources; in Section 5, we summarize our results and conclusions.

2. OBSERVATIONS AND DATA REDUCTION

Observations of the five targets, three INTEGRAL sources and two additional sources from the BAT Galactic plane survey, were conducted between 2006 April 12 and October 31 (see Table 1). On four of the five targets, a single observation was collected while on one source two observations were collected, separated by ~ six months. All sources were observed using the Hard X-ray Detector (HXD) aim point and with the X-ray Imaging Spectrometer (XIS) instruments in normal imaging mode. One of the sources (SWJ1010.1–5747) was found to be a symbiotic star and these observations were published in Smith et al. (2008); this source will not be discussed further here.
Data from the four other targets were reduced using the standard Suzaku processing software, xisrmfit\textsuperscript{6} version 2007-05-14 and xissimarfgen version 2007-09-22 and the other standard analysis tools contained in HEADAS version 6.4. Point-source processing was carried out as described in the Suzaku ABC Data Reduction Guide.\textsuperscript{6} In processing the data each of the two sources whose data are worthy of more detailed characteristics of the sample. We will then focus, in turn, on each of the two sources whose data are worthy of more detailed analysis.

### 3. RESULTS

Two of the sources in our sample show only random temporal variability while two of the sources show important temporal and spectral variations that warrant further discussion. We begin with an overview of the characteristics of each source, considering the observation as a whole, and the global characteristics of the sample. We will then focus, in turn, on each of the two sources whose data are worthy of more detailed analysis.

#### 3.1. Global Fitting

In some cases, fitting a simple absorbed power-law model produces a fit with $\chi^2$ ~ 1, but in all cases a partial covering absorber model is strongly preferred (see Table 2). The partial covering model is invoked here for its ability to quantify interesting parameters from a wide range of geometries using a minimum of fit components. Assuming a dust halo subtending 4\textpi steradians, for example, the partial covering model provides information about the scattering fraction and thus about the density of the halo. Assuming, instead, a geometry similar to accretion disk corona (ADC) systems, the partial covering model provides information about the vertical extent of the ADC and the scale height of the neutral disk material. While the precision of the observations discussed in this paper is too low to confidently distinguish between these different possible geometries, we adopt the use of the partial covering model here to lend our results to future discussion in this context.

The photon index ($\Gamma$) in the partial covering model, ranges from 1.8 to 2.4, the partial covering fraction (PCF) ranges from 0.5 to 0.8 and the $N_H$ column ranges from ~1 $\times$ 10\textsuperscript{23} cm\textsuperscript{-2} to ~1 $\times$ 10\textsuperscript{24} cm\textsuperscript{-2}. These $\Gamma$ are similar to those seen previously in highly absorbed HMXBs (Kuulkers 2005). In one case, the $N_H$ column is slightly below 1 $\times$ 10\textsuperscript{23} cm\textsuperscript{-2} (though within errors; 9 $\times$ 10\textsuperscript{22} cm\textsuperscript{-2}). Since the HXD data for this target, IGRJ16465–4507, are contaminated, however, the high-energy

#### Table 1

| Observational Parameters |
|---------------------------|

| Obsnum        | Source     | Observation Start (Y-M-D-H:M:S) | Observation Stop (Y-M-D-H:M:S) | XIS $\Delta t$ | HXD $\Delta t$ |
|---------------|------------|---------------------------------|---------------------------------|----------------|----------------|
| 401052010     | IGRJ16465–4507 | 06-09-09-09:12:56              | 06-09-22-05:14                  | 14536          | 24645          |
| 401053010     | SWJ2000.6+3210 | 06-04-12-15:53:10              | 06-04-12-21:56:04               | 12444          | 9877           |
| 401053020     | SWJ2000.6+3210 | 06-10-31-00:29:37              | 06-10-31-07:16:19               | 10146          | 11727          |
| 401054010     | IGRJ16493–4348 | 06-10-05-21:10:30              | 06-10-06-10:05:24               | 18975          | 20220          |
| 401055010     | SWJ1010.1–5747 | 06-06-05-05:13:12              | 06-06-05-18:25:25               | 19171          | 20000          |
| 401056010     | IGRJ16195–4945 | 06-09-20-20:25:12              | 06-09-21-17:21:20               | 27908          | 42265          |

#### Table 2

| Source                  | $N_H$ $^{a}$ | $N_{HI}$ $^{b}$ | PCF $^{c}$ | $\Gamma$ $^{d}$ | Flux $^{e}$ | Fe EW $^{f}$ | $\chi^2_{\nu}$ | $\Delta \chi^2_{\nu}$ | dofi $^{i}$ |
|-------------------------|--------------|-----------------|------------|-----------------|------------|-------------|----------------|-----------------------|----------|
| IGRJ16465–4507          | 2.0$^{+0.7}_{-0.9}$ | 7.3$^{+2.8}_{-2.1}$ | 0.82$^{+0.06}_{-0.09}$ | 2.2$^{+0.3}_{-0.4}$ | 8.9$^{+0.5}_{-0.3}$ | <135 | 0.86 | 0.99 | 270 |
| IGRJ16493–4348          | 8.6$^{+0.9}_{-1.0}$ | 26$^{+9.4}_{-7.9}$ | 0.62$^{+0.06}_{-0.07}$ | 2.4$^{+0.2}_{-0.2}$ | 13.5$^{+0.3}_{-2.0}$ | <84 | 0.90 | 1.1 | 389 |
| IGRJ16195–4945          | 11$^{+1}_{-1}$ | 78$^{+17}_{-15}$ | 0.53$^{+0.09}_{-0.10}$ | 1.8$^{+0.1}_{-0.1}$ | 16.1$^{+0.2}_{-2.2}$ | <43 | 0.93 | 1.0 | 614 |
| SWJ2000.6+3210(1)       | 2.3$^{+0.5}_{-0.2}$ | 9.3$^{+1.2}_{-0.9}$ | 0.68$^{+0.03}_{-0.02}$ | 2.2$^{+0.1}_{-0.1}$ | 32.0$^{+0.5}_{-0.9}$ | 51$^{+34}_{-27}$ | 0.92 | 1.6 | 417 |
| SWJ2000.6+3210(2)       | 2.1$^{+0.2}_{-0.2}$ | 8.2$^{+1.0}_{-1.0}$ | 0.70$^{+0.02}_{-0.03}$ | 2.0$^{+0.1}_{-0.1}$ | 55.0$^{+0.8}_{-0.6}$ | 71$^{+28}_{-29}$ | 0.90 | 1.7 | 725 |

Notes.

- $^{a}$ Fully covered neutral hydrogen column $\times 10^{22}$ cm\textsuperscript{-2}.
- $^{b}$ Partially covered neutral hydrogen column $\times 10^{22}$ cm\textsuperscript{-2}.
- $^{c}$ Partially covering fraction.
- $^{d}$ Photon index.
- $^{e}$ Flux in range 0.2 keV to 10 keV $\times 10^{-12}$ erg cm\textsuperscript{-2} s\textsuperscript{-1}.
- $^{f}$ 6.4 keV Fe line equivalent width in eV.
- $^{g}$ Reduced $\chi^2$ of partial covering fit.
- $^{h}$ Reduced $\chi^2$ of simple absorbed power-law fit.
- $^{i}$ Degrees of freedom in partial covering fit.
spectral slope for this source is not as well constrained as it is for the others, probably leading to an unusually high value of the PCF compared to the other sources. The higher PCF suppresses the soft X-ray flux which helps to explain the lower $N_H$ column in this source. As a simple test of the effect of fitting IGRJ16465–4507 without the HXD data, we have fit each of the other three sources using the XIS data alone. In each case, fitting to XIS data alone results in a flatter power-law index, a higher PCF or both. Either increasing the photon index or decreasing the PCF in the fit of IGRJ16465–4507 to a similar degree as is seen in the behavior of the other sources leads to an increase in the $N_H$ column of the former to a value of $\sim 1.5 \times 10^{23}$ cm$^{-2}$. Therefore, the $N_H$ column value listed in Table 2 should likely be considered only a lower limit to the true value.

All sources show variability on timescales of hundreds of seconds. Furthermore, IGRJ16195–4945 shows a bright outburst lasting $\sim 5000$ s and SWJ2000.6+3210 shows periodic variations. We will return to discuss these two objects in greater detail shortly. Overall flux levels range from $1 \times 10^{-11}$ to $5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ (absorbed) in the 0.2–10 keV energy band.

As a check of consistency, we have compared our results with previous work on these sources as noted below. Comparing to absorbed cutoff power-law fits by Kuulkers (2005, K05 hereafter), our best-fit results for IGRJ16195–4945 match well. Comparing our 0.2–10 keV data to the Chandra absorbed power-law fits in Tomsick et al. (2006) also produces good agreement in spectral shape, though we find a flux $\sim 5$ times brighter than they do. Our best-fit results for IGRJ16195–4348 do not match those of K05, but if we fix $\Gamma$ to be similar to that found by K05, we find a column density similar to theirs and can additionally note a cutoff energy of 17.5 keV. We also compare to the results of absorbed power-law fits to Rossi X-Ray Timing Explorer (RXTE) data on this source (Markwardt et al. 2005a) finding good agreement with their fit of $N_H \sim 10^{23}$ and $\Gamma \sim 1.4$ with a 2–10 keV flux $\sim 1 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$. Our best-fit results of IGRJ16465–4507 do not match that of K05. Even after fixing $\Gamma$ and the cutoff energy to match that of K05, the $N_H$ column that we find is still more than an order of magnitude lower than that found by K05. We also compare our results to Walter et al. (2006) where we once again find that our intrinsic column density is an order of magnitude lower than they find. While contamination of the high energy data may account for some of the discrepancy between our results and previous work in this case, we also note that we see no evidence in our data of the $\sim 4$ minute period noted by K05. This suggests that our data may be taken during the apoapoastron phase of an elliptical binary orbit when the flux level, spectrum, and absorption column have different values than they do near periastron, where the higher wind density may produce periodic variations like those reported in the K05 observation. Thus, it is not surprising that our observations of this source appear different. In general, however, our overall results appear consistent with previous work.

Swift–BAT data from the forthcoming 22 month survey (Tuluer et al. 2009) have been analyzed for each of the sources in our sample. No evidence of outbursts on daylong timescales (similar to those seen in the Suzaku observation of IGRJ16195–4945, e.g.) are found. The BAT daily survey detection threshold is $\sim 5–10$ mcrab (Markwardt et al. 2005b), however, so the nondetection of the $\sim 100–500$ mcrab outbursts seen in our Suzaku data is not surprising. We have, furthermore, examined the BAT data binned over longer timescales (2, 4, 8, 16, 32, and 64 days) to improve the sensitivity of our variability search. While all sources show stochastic variability on these timescales, no evidence of periodicity is seen.

For the three sources with uncontaminated BAT data, we have made simultaneous fits with the Suzaku and BAT data. In the cases of IGRJ16493–4348 and SWJ2000.6+3210, the BAT data are well fit by the same model derived from fitting the Suzaku data alone. This implies that the snapshot captured in the Suzaku observations of these two sources is representative of the overall source behavior and shows that the partial covering scenario is supported to energies as high as 200 keV. In the case of IGRJ16195–4945, the BAT data are not well fit to the same spectrum as the total Suzaku observation, nor to any of the fragmented spectra shown in Table 5. Since the total Suzaku observation does not match the BAT data, we can infer that flares such as that seen in the Suzaku data do not dominate the flux from the source. Since the BAT data are also not well fit by the spectrum seen in the Suzaku quiescent data (the BAT data fit a softer spectrum than any segment of the Suzaku data and have a higher intensity than the quiescent segment but lower intensity than the post-flare segment), we can also infer that the quiescent state is not highly representative of this source. Since the post-flare state is also a poor fit to the BAT data, we infer that the source spends more time in the quiescent state than is seen in the Suzaku observation, but that flares such as that seen in the Suzaku data are somewhat common (since the quiescent state does not match the BAT data). We will discuss this in further detail in Section 4.

Spectra and light curves (in cases where the light curve shows noteworthy behavior) of each source are shown in Figures 1–5. In the spectral plots, black data points show Suzaku data while green data points show the average BAT 22 month survey data for comparison. We note that the spectral fits detailed in Tables 2, 4, and 5 are derived using Suzaku data only.

### 3.2. IGRJ16195–4945

The light curve of IGRJ16195–4945 is marked by a short, bright flare, seen in both the XIS and HXD instruments. The flare lasts for $\sim 5000$ s and reaches a peak flux level $\sim 10 \times$
Figure 2. IGRJ16465–4507 spectrum in the 0.2–10.0 keV energy range. Low-energy data are from the XIS0, XIS1, XIS2, and XIS3 instruments. High-energy data from the HXD-PIN are contaminated by a bright serendipitous source and are therefore not included in the analysis.

(A color version of this figure is available in the online journal.)

Figure 3. IGRJ16195–4945 light curve (top) and total spectrum in the 0.2–150.0 keV energy range (bottom). Suzaku data are shown in black while BAT data are shown in green. Data are extracted and analyzed over the entire data set but also in each of the data subsets shown in the figure by numbered red lines. The numbered segments correspond to separated fits as shown in Tables 4 and 5.

(A color version of this figure is available in the online journal.)

Figure 4. SWJ2000.6+3210 light curve (top) and spectrum in the 0.2–150.0 keV energy range (bottom) from observation 1. Suzaku data are shown in black while BAT data are shown in green. The light curve is shown here, where no periodic variability is seen, for comparison to the second observation, where periodicity is apparent.

(A color version of this figure is available in the online journal.)

brighter than the prior emission level. This duration and flaring/quiescent flux ratio is characteristic of the subset of HMXBs known as supergiant HMXBs (sgHMXBs, Walter & Zurita Heras 2007). To better understand the nature of the flare and how it compares to the source during quiescence, we have separated the data as shown in Figure 3 and Table 3. The data segmentation separates the period prior to the flare (quiescence) from the flare itself (flare) and from the period after the flare has decayed to near the original level (post-flare). The definition of the quiescent period is clear due to an extended gap in the data (20 ks) prior to the onset of the flare. The definition of the end of the flare is less clear, but we have chosen to define it with the end of the orbit during which the flare decays below \(\sim 2\times\) the original level. The subsequent data to the end of the observation are defined as post-flare. This definition ensures that the flare segment is dominated by flare emission even if some small amount of post-flare emission is included. It also ensures that the post-flare data are sufficient to produce an accurate spectrum. We have further subdivided the flare into the rising leg of the flare, the decaying leg of the flare (which are conveniently separated by an orbital gap) and a segment that encompasses all data from the onset of the flare to the end of the observation (“on”).
Figure 5. SWJ2000.6+3210 light curve (top left), folded light curve (top right), and spectrum in the 0.2–150.0 keV energy range (bottom) from observation 2. Suzaku data are shown in black while BAT data are shown in green. Periodicity that may be seen in the raw light curve is made apparent in the folded light curve. (A color version of this figure is available in the online journal.)

Table 3

| Segment       | Start (s) | Stop (s) | Duration (s) |
|---------------|-----------|----------|--------------|
| Quiescence    | 0         | 12000    | 12000        |
| Total flare   | 40068     | 46684    | 6616         |
| Flare onset   | 40068     | 41769    | 1701         |
| Flare decay   | 44669     | 46684    | 2015         |
| Post-flare    | 49000     | 72000    | 23000        |
| On            | 40068     | 72000    | 31932        |

Note. Data from IGRJ16195–4945 are segmented to separate the period prior to the flare (quiescence) from the flare itself (flare) and from the period after the flare has decayed to near the original level (post-flare).

The results of absorbed power-law and partial covering model fits to each of the six segments (quiescence, total flare, flare onset, flare decay, post-flare, on) are shown in Table 4. To limit the number of free parameters in the fit we have fixed the global $N_H$ column density, the partial covering column, and the PCF to the values that they have when fitting the complete observation, allowing only $\Gamma$ to vary. We will return momentarily to the possibility that the spectral variation is due to these other parameters.

When allowing only $\Gamma$ to vary, we find that the “on” segment is well fit by a model with $\Gamma \sim 1.8$. The quiescent data, in contrast, are fit by a much softer $\Gamma \sim 2.5$. No significant Fe lines are seen, although upper limits are given in Table 4. It is interesting to note that $\Gamma$ remains nearly unchanged (perhaps even becoming harder) as the flare subsides and the post-flare phase begins.

Considering the modest flux level of the post-flare phase, one would expect that as the flare decays the spectrum would soften as the quiescent component once again becomes comparable to the flaring component. That this is not seen suggests that, during the post-flare phase, the emission component that was seen during the quiescent phase is not merely being overwhelmed by the component responsible for the flare emission, but rather is absent altogether.

If we leave all components of the partial covering model free to vary we find the results shown in Table 5. Here, we see the quiescent phase described by a high PCF, moderately hard power law and low column density. In contrast, the flare shows a low PCF and softer power law with much higher column density. Finally, the post-flare phase shows a PCF between the other two, the softest $\Gamma$ and the highest column density of all the segments. This suggests that the flare signals the onset of emission from a region of greater local column density, possibly due to interaction with dense clumps in the donor star wind (see, e.g., Walter & Zurita Heras 2007; Negueruela et al. 2008) or to interaction with a donor star disk (Sidoli et al. 2007). We will return to discuss these possibilities in Section 4.

Previous observations of this source by both ASCA (Sidoli et al. 2005) and INTEGRAL (Sguera et al. 2006) have also shown evidence of outbursts lasting ~1–2 hours. Translated into a common energy range, the flux of these previous outbursts is lower than that seen in our Suzaku observations by a factor of a few, but differences in the measured spectral parameters and the lower signal to noise of these earlier observations limit the precision of the comparison. Nevertheless, the similarity of the outbursts in these three observations seems suggestive either of
previous work has identified both IGRJ16195–4945 and J164422–6331 as objects with high variability in their X-ray emission. These observations may suggest that the system is in an elliptical orbit.

3.3. SW2000.6+3210

Data were collected on SWJ2000.6+3210 during two epochs, separated by six months (see Figures 4 and 5). We have analyzed each of these observations separately. Neither observation is adequately fit by a simple absorbed power law (see Table 2). Both observations are well fit by a partial covering model and the parameters of the fits are similar. The later observation has a slightly harder $\Gamma$ and significantly larger flux. Both observations show evidence of a weak Fe fluorescence line at 6.4 keV with apparently constant equivalent width.

Interestingly, while the first observation shows only random variability, the second observation shows regular variations with a period of 1056 s. We interpret this as the spin period of the neutron star companion in a binary, similar to long periodic variations noted in several other INTEGRAL discovered sources (see, e.g., Bird et al. 2007; Bodaghee et al. 2007). There is the suggestion of secular variation beneath the 1056 s period, but the data are insufficient to confidently determine any further periodic components.

These observations may suggest that the system is in an elliptical orbit. During the first observation, the compact object is far from the donor star where the wind density is low. In this case, the X-ray flux is likely to be approximately constant, possibly associated with an accretion disk or corona around the compact object. During the second observation, the compact object is nearer to the donor star where the stellar wind is more dense, channeling more material onto the neutron star and producing the observed periodicity associated with the neutron star rotation.

4. DISCUSSION

Previous work has identified both IGRJ16195–4945 and IGRJ16465–4507 as likely absorbed sgHMXBs (see, e.g., Walter et al. 2006; Walter & Zurita Heras 2007; Rahoui et al. 2008; Bodaghee et al. 2007; Tomsick et al. 2006).
confirm these observations with the Suzaku data presented here and identify SWJ2000.6+3210 as also consistent with the absorbed sgHMXB source subclass. The moderately high \( N_H (\sim 1 \times 10^{23} \text{ cm}^{-2}) \), \( \Gamma \) and cutoff energy of this source are similar to other members of the subclass and it shows periodic variations with a period of 1056 s, also similar to other members of the group. While the nature of IGR16493–4348 is not tightly constrained by these soft X-ray observations alone, it does display a high neutral hydrogen column density and some evidence of stochastic variability, potentially suggesting it too as a member of the absorbed sgHMXB group.

IGRJ16195–4945 shows a high absorbing column and a brief but bright X-ray outburst, adding evidence for its SFXT nature as a member of the absorbed sgHMXB group. Nevertheless, significantly larger than the 18.5 days reported by Rahoui & Chaty (2008) or the 16 day possible period suggested here for IGRJ16195–4945 (having an average period of 78 days and none shorter than 55 days), the notion of an intermediate group of sources was further developed by Negueruela et al. (2008) into a potential unification scheme in which sgHMXBs, intermediate SFXTs, and normal SFXTs are related by orbital radius or eccentricity or both. We are pursuing further observations to follow-up this predicted orbital period. If the predicted period is shown to be accurate, IGRJ16195–4945 would be the second such intermediate source with a period of \( \sim 20 \) days and would provide evidence in support of such a unification scenario. If the period is shown to be accurate, it would also suggest a useful method of refining the period search for such sources in instances where a single flare has been observed but large amounts of observational time are not available for a dedicated follow-up monitoring campaign. A long-term monitoring campaign of this source would be very useful to determine the true duration of the associated outbursts.

To estimate the flux levels \( a, b, c, \) and \( d \), we fit each corresponding data set using the average spectral fit to the complete data set (including the BAT data) and determined the associated flux level in the 15–150 keV band. We find \( a = 5.13 \times 10^{-12}, b = 8.61 \times 10^{-11}, c = 3.93 \times 10^{-10}, \) and \( d = 3.11 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1} \). Using these values with Equation (2) returns a predicted period \( P \sim 16 \) days. This period is unusually short compared to other measured SFXT periods (Zurita Heras et al. 2007; Romano et al. 2007). Even if we alter our calculation to interpret the on state (see Tables 4 and 5) as the measure of the flux during the passage through the disk wind rather than weighting it heavily to the post-flare state as shown above, the predicted period only increases by a factor of \( \sim 2 \), which is still well below the more typically reported SFXT orbital periods of \( \geq 200 \) days. The 18.5 day orbital period of IGR18483–0311, originally reported by Levine & Corbet (2006), has recently been used by Rahoui & Chaty (2008), together with its unusually long flares and high quiescence level, to propose it as an “intermediate” SFXT. Such a group of intermediate objects, falling between the sgHMXBs and SFXTs both in terms of orbital period and flaring behavior, was identified by Walter & Zurita Heras (2007) to describe sources showing similar flaring behavior to SFXTs but at lower ratios of peak flaring to quiescent flux. While the orbital periods of the intermediate sources in their sample are, nevertheless, significantly larger than the 18.5 days reported by Rahoui & Chaty (2008) or the 16 day possible period suggested here for IGRJ16195–4945 (having an average period of 78 days and none shorter than 55 days), the notion of an intermediate group of sources was further developed by Negueruela et al. (2008) into a potential unification scheme in which sgHMXBs, intermediate SFXTs, and normal SFXTs are related by orbital radius or eccentricity or both. We are pursuing further observations to follow-up this predicted orbital period. If the predicted period is shown to be accurate, IGRJ16195–4945 would be the second such intermediate source with a period of \( \sim 20 \) days and would provide evidence in support of such a unification scenario. If the period is shown to be accurate, it would also suggest a useful method of refining the period search for such sources in instances where a single flare has been observed but large amounts of observational time are not available for a dedicated follow-up monitoring campaign. A long-term monitoring campaign of this source would be very useful to determine the true duration of the associated outbursts.

IRGJ16493–4348 is a variable source with a high column density and nonperiodic variations, also potentially qualifying it with the sgHMXB subclass. Finally, IGRJ16465–4507 presents the fewest similarities to previous observations of either sgHMXBs or SFXTs. Due to the narrow energy window in which our observations are made for this source, however, our measurements are not as constraining as for the other sources. We note that we do not see periodic variability in this source as previously reported by others (Lutovinov et al. 2005; Kudryavtsev et al. 2006).

Two of the four sources in our sample appear to be transient pulsars: IGRJ16465–4507, for which transient periodicity has previously been reported by Walter et al. (2006), and Swift J2000.6+3210. This agrees with the global fraction of INTEGRAL detected HMXBs which have identified spin periods (Bodaghee et al. 2007) of slightly more than half (54%). The transient nature of the spin period in these two sources is suggestive that they are both in elliptical orbits around the companion. The relationship between the geometry of the binary orbit and the observed characteristics of the sgHMXB and
SFXT subclasses is currently under active investigation (see, e.g., Negueruela et al. 2008; Prat et al. 2008; Rahouï & Chaty 2008; Sidoli et al. 2007). Since it has been shown that binaries will circularize rapidly (\(10^8\)–\(10^9\) years) through tidal dissipation following the supernova detonation of the more massive star (Savonije & Papaloizou 1983; Lecar et al. 1976), the occurrence of highly elliptical orbits, if found to be common in these sources, will require explanation. As a rough estimate of the fraction of sources that may be expected to be in highly elliptical orbits, we may proceed from work showing that the companion in several of these systems is a supergiant O or B star (Chaty et al. 2008; Nespoli et al. 2008; Rahouï et al. 2008; Tombsick et al. 2006). This implies that the HMXB phase of the lifetime of the system (the time after the detonation of the more massive star and prior to the detonation of the less massive star) will be typically (5–10) \(\times\) \(10^8\) years. Therefore, at most 10%–20% of the observed sources should be found in strongly elliptical orbits. Finding a significantly higher fraction of highly elliptical orbits would suggest another mechanism at work during the HMXB evolution. Possible explanations for the lower circularization rate include generally wide orbital separation of the binaries, unusually large initial supernova kicks, and capture events or other gravitational interactions that may amplify the eccentricity of the system.

It has been shown by Abt (2005) that the ellipticity of visual binaries is roughly a function of the mass of the primary and the orbital period of the system, with tidal dissipation responsible for rapid circularization of systems with orbital periods less than about 10 days. Since the same mechanism of tidal dissipation is thought to be responsible for the circularization of X-ray binary orbits, it seems reasonable to assume that a similar function applies to HMXBs. Measuring both the ellipticity of the orbit and the period for a sample of these systems through a monitoring campaign would provide a test of this hypothesis and thus would indicate whether tidal dissipation is the dominant effect in HMXB circularization.

Monitoring would also determine orbital periods of each system, a necessary step toward determining the orbital characteristics of the system and ultimately the mass of the compact object, and would allow a more in-depth analysis of spectral variability as a function of orbital phase. Since the neutron stars in these binaries likely orbit only a few stellar radii from the companion and are thought to have orbital periods on the order of 10 days, daily or perhaps semimonthly observations for about a month seem sufficient to accurately determine all of these characteristics. The Swift satellite offers the capability to perform such monitoring and, with its simultaneous X-ray and optical observations, would provide an ideal platform for future observations. Finally, monitoring on long timescales (covering a baseline of several years) will allow investigation of the spin-up/spin-down of the pulsar which can shed light on its magnetic field strength and on the wind environment in which it is embedded (see, e.g., Patel et al. 2007).

Three of the four sources in our sample are confidently associated with OB stars from optical spectroscopy (Negueruela et al. 2005; Halpern 2006; Nespoli et al. 2008). In the case of IGRJ16195–4945, a foreground dwarf star has thwarted attempts to identify the secondary. IGRJ16195–4945 has a history of X-ray outbursts, however, which are a trait of SFXTs that contain OB secondary stars (Negueruela et al. 2006). Thus, association with a massive star seems likely for this system as well.

Since the companion stars in these sources are most likely O or B stars, an interesting potential application of these data is to study the porosity or clump size of the absorbing material in the winds of massive stars. Though the periodic variability and extremely bright outbursts seen in some of the data cannot be explained by variations in the column density along the line of the sight to the observer in classic HMXBs, stochastic variations of lower contrast, which are also seen in the data, are a potential signature of variable obscuration. We have searched for variations in column density (assuming all other spectral parameters remain constant as a simplifying approximation) during the aperiodic pulses seen in some of the data but do not find any to within the uncertainty of the data. We point out, however, that typical fluxes in the pulses analyzed are <1000 photons, leading to weak constraints on the column density. While some of these sources have prior observations with RXTE, whose greater effective area will reduce the uncertainty in these measurements, the exposures are extremely short (3–4 ks) and thus are not able to constrain column density variations on timescales of 5–10 ks as seen in these data. Longer observations of these sources with XMM-Newton would be useful in this regard and would offer the additional benefit of high-resolution soft X-ray spectroscopy to probe the ionization state of the wind through metal line strengths. Walter & Zurita Heras (2007) have investigated the size of clumps in the accreting wind of SFXTs and determined typical masses of \(10^{22}\)–\(10^{23}\) g and mass-loss rates of \(10^{-5}\)–\(10^{-6}\) \(M_\odot\) yr\(^{-1}\) from analysis of INTEGRAL data. INTEGRAL data do not constrain \(N_H\), however, and thus cannot distinguish between variability due to changing column density levels and that due to changing accretion levels. Prat et al. (2008) have shown through combined INTEGRAL and RXTE monitoring of the HMXB IGRJ19140+0951 that the \(N_H\) column density of that source seems to be correlated with orbital phase, as does the appearance of an apparent soft X-ray excess, with the maximum of both features occurring near superior conjunction. They use these results to support a model in which the \(N_H\) absorption is due to the integrated column through the wind of the supergiant companion star and the soft X-ray excess is due to scattering of X-rays (from the companion or the primary or both) off an ionized “tail” trailing the neutron star. They note, however, that the soft X-ray sensitivity and resolution of RXTE are not sufficient to accurately constrain the geometry of the orbit with respect to the wind density and thus that their model remains speculative. XMM-Newton observations at 0.2–10.0 keV may help to distinguish whether the variability is due to changing accretion levels or due to variable obscuration. RGS observations could be very useful in identifying the ionization state of a soft X-ray excess as noted by Prat et al. (2008) in the case of IGRJ19140+0951, thus helping to confirm or counter this model.

The limits on the Fe line equivalent widths (EWs) found in these sources are low for sources of such high \(N_H\) column density (Makishima 1986). Such low Fe line EWs imply either an intrinsically low Fe abundance relative to \(N_H\) (as has been seen in extragalactic sources, e.g., Centaurus A, Markowitz et al. 2007) or that the Fe fluorescence covering fraction is less than 1. If the high \(N_H\) column density absorber is local to the compact object, as has been suggested through comparisons between X-ray and optical absorption measures (e.g., Revnivtsev et al. 2003; Walter et al. 2003; Chaty & Filliatre 2004), and if the Fe fluorescence originates in a shell structure surrounding the
compact object, it is difficult to envision a geometry in which the coverage would be less than $4\pi$. The Fe emission may originate in the inner region of the accretion disk, however, in which case a lower covering fraction may be reasonable. Furthermore, there are reasons to believe that the assumptions inherent in relating X-ray and optical absorption measures may not be valid for all sources (Maiolino et al. 2001), and thus the disagreement between X-ray and optical absorption measures may not necessarily imply that the high column absorber is local to the compact object. Alternatively, such low Fe EWs might also be considered as evidence of the presence of ADC emission. The presence of an ADC seems unlikely, however, given the lack of other emission lines from 1 to 5 keV that they usually produce. Still other explanations for low Fe EWs are similar to those discussed by Markowitz et al. (2007) in reference to Cen A and include the Fe fluorescence source being displaced from the X-ray continuum source or the presence of an attenuating obstruction between the X-ray source and the site of the Fe fluorescence. While our data argue against (but do not rule out) the low covering fraction scenario, the intrinsically low Fe EWs scenario requires nontrivial assumptions about the geometry of the system. Further observations, particularly phase-resolved spectroscopy, will be very helpful in disentangling these many potential explanations.

5. SUMMARY AND CONCLUSIONS

Our primary goal in this study is to determine whether these four sources exhibit similar characteristics to the emerging subclasses of highly absorbed IGR sgHMXB or SFXT sources. The defining characteristics of these subclasses are (1) high absorption column ($\gtrsim 1 \times 10^{23}$ cm$^{-2}$), (2) periodicity on timescales of a few to $\sim 100$ minutes, generally interpreted as a neutron star spin period, (3) periodicity on timescales of $\sim 10$ days, generally interpreted as a binary orbital period, and (4) occasionally strong X-ray emission lines.

1. In all four sources the total absorbing column is $\gtrsim 1 \times 10^{23}$ cm$^{-2}$. Generally, we do not see significant changes in the absorption over the duration of the observations. While this is not surprising during a single day-long observation, which probably samples a small segment of the orbital phase, it is somewhat surprising that two observations of SWJ20006+3210, separated by more than six months (and furthermore apparently at different parts of the orbital phase) also show no significant difference in $N_H$. A dramatic increase in absorbing column is seen in IGR16195–4945 for a duration of $\sim 30$ ks, during a bright outburst (when all parameters are left free to vary). Since this dramatic increase in $N_H$ is associated with a dramatic increase in flux, one might interpret this as an increase in emission due to interaction of the neutron star with a density enhancement. Such a scenario might be expected due to the passage of the neutron star through a thick disk associated with the donor star. Since an interpretation in which $N_H$ is approximately constant and only $\Gamma$ varies also produces adequate spectral fits, an alternative model in which the increased emission is due to variable accretion is also possible.

2. In SWJ20006+3210, we see a period of 1056 s which is only observed during one of two observations of the source. This is a newly identified transient X-ray pulsar. Given the low magnetic field implied by the relatively slow rotation period of 1056 s, it is not surprising that the same mechanism that produces periodic observations near periastron is too weak to produce an observable period near apoastron where the wind density will be lower.

3. Due to the short nature of the observations (generally $\sim 1$ day), we do not expect to directly measure orbital periods, previously reported to be on the order of 10 days in other sgHMXBs and, indeed, we do not. During observations of the one source for which we have well separated observations we also do not see evidence of an orbital period. We have, however, used our observations to calculate a predicted orbital period for IGRJ16195–4945. Assuming that IGRJ16195–4945 is a SFXT and that the bright flare we see signals the interaction of the compact object with an equatorial wind of the donor star, we have combined our Suzaku observations with long-term Swift-BAT observations to predict the orbital period for this source as $P \sim 16$ days. This is unusually short compared to previously measured SFXT orbital periods, but is consistent with orbital periods previously measured for the highly absorbed IGR sources. This source may be an example of an “intermediate” SFXT, similar to IGR18483–0311 as discussed by Rahoui & Chaty (2008). More consistent monitoring, perhaps using the Swift satellite (see, e.g., Romano et al. 2009), would be very useful in confirming or refuting this predicted period and in characterizing the orbital periods of these highly absorbed binaries in general.

4. We find only weak evidence of Fe fluorescence emission in one source, and only upper limits to Fe lines in the other three sources. This is similar to the behavior reported in the original INTEGRAL highly absorbed X-ray binary sources (Kuulkers 2005) in which only 1 of the 10 sources showed strong emission lines while the others showed only weak lines or upper limits. The Fe line measurements that we report here are either the first for the source in the literature (IGRJ16465–4507, IGRJ16493–4348, Swift J2000.6+3210) or several times more restrictive than previous measurements (IGRJ16195–4945). Moreover, our measurements are similarly or more restrictive than those reported on similar sources in the literature (see, e.g., Sidoli et al. 2005; Patel et al. 2004; Rodriguez et al. 2003).

We are grateful to Hans Krimm and Gerry Skinner for providing access to and help in analyzing the BAT survey data and to Fotis Gavril for help in the timing analysis studies. We also thank Maurice Leutenegger for useful discussion and comments. D.C.M. acknowledges support from the Center for Nuclear Studies (CNS) through the Research Enhancement Fund at the George Washington University and from NASA grant NNH05ZDA001N-SUZ/11132.

REFERENCES

Abt, H. A. 2005, ApJ, 629, 507
Bird, A. J., et al. 2004, ApJ, 607, L33
Bird, A. J., et al. 2007, ApJS, 170, 175
Bodaghee, A., et al. 2007, A&A, 467, 585
Chaty, S., & Filliatre, P. 2004, in Proc. 5th INTEGRAL Workshop on the INTE-GRAL Universe, ed. V. Schönfelder, G. Lichit, & C. Winkler (Noordwijk, ESA), 365
Chaty, S., et al. 2008, A&A, 484, 783
Filliatre, P., & Chaty, S. 2004, ApJ, 616, 469
Halpern, J. P. 2006, Astron. Telegr., 847, 1
Kudryavtsev, M. I., Sverbylov, S. I., & Bogomolov, V. V. 2006, arXiv:astro-ph/0610857
Kuulkers, E. 2005, in Proc. AIP 797, Interacting Binaries: Accretion, Evolution, and Outcomes, ed. L. Burderi et al. (Melville, NY: AIP), 402
Lecar, M., Wheeler, J. C., & McKee, C. F. 1976, ApJ, 205, 556
Levine, A., & Corbet, R. 2006, Astron. Telegr., 940, 1
Lutovinov, A., et al. 2005, A&A, 444, 821
Maiolino, R., et al. 2001, A&A, 365, 28
Makishima, K. 1986, in Lecture Notes in Physics, Vol. 266, The Physics of Accretion onto Compact Objects, ed. K. P. Mason, M. G. Watson, & N. E. White (Berlin: Springer), 249
Markowitz, A., et al. 2007, ApJ, 665, 209
Markwardt, C. B., et al. 2005a, Astron. Telegr., 465, 1
Markwardt, C. B., et al. 2005b, ApJ, 633, L77
Matt, G., & Guainazzi, M. 2003, MNRAS, 341, L13
Negueruela, I., Smith, D. M., & Chaty, S. 2005, Astron. Telegr., 429, 1
Negueruela, I., et al. 2006, in Proc. The X-Ray Universe 2005, ed. A. Wilson (ESA SP-604; Noordwijk: ESA), 165
Negueruela, I., et al. 2008, in Proc. AIP Conf. Ser. 1010, A Population Explosion: The Nature and Evolution of X-Ray Binaries in Diverse Environments, ed. R. M. Bandyopadhyay et al. (Melville, NY: AIP), 252
Nespoli, E., Fabregat, J., & Meninkent, R. E. 2008, A&A, 486, 911
Patel, S. K., et al. 2004, ApJ, 602, L45
Patel, S. K., et al. 2007, ApJ, 657, 994
Pellizza, L. J., Chaty, S., & Negueruela, I. 2006, A&A, 455, 653
Prat, L., et al. 2008, MNRAS, 389, 301
Rahoui, F., et al. 2008, A&A, 484, 801
Rahoui, F., & Chaty, S. 2008, A&A, 492, 163
Revnivtsev, M. G., et al. 2003, Astron. Lett., 29, 587
Rodriguez, J., et al. 2003, A&A, 407, L41
Romano, P., et al. 2007, A&A, 469, L5
Romano, P., et al. 2009, in Proc. 7th Integral Workshop, in press (arXiv:0902.1988)
Savonije, G. J., & Papaloizou, J. C. B. 1983, MNRAS, 203, 581
Sguera, V., et al. 2006, ApJ, 646, 452
Sidoli, L., et al. 2005, A&A, 429, 47
Sidoli, L., et al. 2007, A&A, 476, 1307
Smith, R. K., et al. 2008, PASJ, 60, 43
Tomsick, J. A., et al. 2006, ApJ, 647, 1309
Tomsick, J. A., et al. 2008, ApJ, 685, 1143
Tueller, J., et al. 2009, arXiv:0903.3037v1
Walter, R., et al. 2003, A&A, 411, L427
Walter, R., et al. 2006, A&A, 453, 133
Walter, R., & Zurita Heras, J. 2007, A&A, 476, 335
Winkler, C., et al. 2003, A&A, 411, L1
Zurita Heras, J. A., Chaty, S., & Rodriguez, J. 2007, Astron. Telegr., 1035, 1