SIMULTANEOUS X-RAY AND OPTICAL OBSERVATIONS OF EX HYDRAE

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ABSTRACT

The intermediate polar, EX Hydrae, was the object of a large simultaneous multiwavelength observational campaign during 2000 May–June. Here we present the Rossi X-Ray Timing Explorer photometry and optical photometry and spectroscopy from ground-based observatories obtained as part of this campaign. Balmer line radial velocities and Doppler maps provide evidence for an extended bulge along the outer edge of the accretion disk and some form of extended/overflowing material originating from the hot spot. In addition, the optical binary eclipse possesses an extended egress shoulder, an indication that an additional source (other than the white dwarf) is coming out of eclipse. We also compare the X-ray and optical results with the results obtained from the EUV and UV observations from the multiwavelength data set.

Key words: accretion, accretion disks — novae, cataclysmic variables — stars: individual (EX Hydrae) — X-rays: stars

1 INTRODUCTION

Intermediate polars (IPs) are a class of magnetic cataclysmic variables (CVs) in which an asynchrornously rotating white dwarf accretes matter from an accretion disk via magnetically controlled accretion curtains. Modulations observed over the white dwarf spin period in IPs are generally attributed to either photoelectric absorption by the accretion curtain (the accretion curtain model; Cordova et al. 1985; Rosen et al. 1988) or to a self-eclipse of the lower accretion pole by the white dwarf (e.g., Beuermann & Osborne 1988). Over the binary orbital period, the observed modulation is due to the properties of a typical CV (accretion disk, eclipses by the secondary) and eclipses of the emitting regions close to the white dwarf surface.

Here we report on simultaneous X-ray and optical photometric and optical spectroscopic observations of the IP EX Hydrae. EX Hya has a spin period of 67 minutes (the spin phase is denoted as $\phi_{WD}$ throughout) and a binary orbital period of 98 minutes (binary phase is denoted as $\phi_{ORB}$ throughout). The mass of the white dwarf has yet to be constrained completely, as optical and UV studies give $M_{WD} \sim 0.8 M_{\odot}$ (e.g., Hellier et al. 1987; Belle et al. 2003), while X-ray studies give $M_{WD} \sim 0.5 M_{\odot}$ (e.g., Fujimoto & Ishida 1997; Hoogerwerf et al. 2004). Reports on recent X-ray spectroscopic observations of EX Hya can be found in Mauche et al. (2001, 2003), Mukai et al. (2003), and Hoogerwerf et al. (2004). Mauche et al. (2001, 2003) find that the hot, $T_e \sim 12$ MK, emitting plasma in the accretion column has an electron density of $n_e = 1.0^{+2.0}_{-0.5} \times 10^{14}$ cm$^{-3}$, using Chandra High Energy Transmission Grating (HETG) spectra. Mukai et al. (2003) find that the Chandra HETG spectrum of EX Hya can be fit with a simple isobaric cooling flow model. Hoogerwerf et al. (2004) use the Chandra spectrum to find a radial velocity and mass for the white dwarf, $K_1 = 58.2 \pm 3.7$ km s$^{-1}$ and $M_{WD} = 0.49 \pm 0.13 M_{\odot}$.

This paper is the third and final paper in a series detailing simultaneous multiwavelength observations of EX Hya. In the first paper (Belle et al. 2002), we reported on observations with the Extreme Ultraviolet Explorer (EUEV); its one million seconds of photometry and spectroscopy of EX Hya provided the basis for the multiwavelength observations. The EUV photometry revealed the presence of two dips in the binary light curve, whose absorption depths changed with spin phase. Our second paper (Belle et al. 2003) presented Hubble Space Telescope (HST) spectroscopy of EX Hya. The mass of the white dwarf was calculated as $M_{WD} = 0.91 \pm 0.05 M_{\odot}$ from the $K$ amplitude of the radial velocity curve of the narrow UV emission lines. Spectral model fits to the UV data also produced the same mass white dwarf with $T = 23.000$ K and an accretion disk truncated at 2.5$R_{WD}$.

2 OBSERVATIONS

As part of a simultaneous multiwavelength observational campaign of EX Hya (executed in 2000 May–June; see Belle et al. 2002, 2003), we obtained X-ray photometry from the Rossi X-Ray Timing Explorer (RXTE) satellite, optical spectroscopy from Apache Point Observatory (APO), and optical photometry from Braeside Observatory (BO) and Rosemary Hill Observatory (RHO). Table 1 gives a complete list of the simultaneous EX Hya observations completed during 2000 May–June; those marked with an asterisk are presented in this paper.

RXTE observed EX Hya for 15 ks over four separate observations using the Proportional Counter Array, which consists of five Proportional Counter Units (PCUs). During the observations, only PCU2 and PCU3 were in continuous operation, so we present here only the data from these two PCUs. The data set spans the wavelength range 1–5 Å (12.4–2.5 keV) and provides complete coverage of the spin period but only partial coverage of the...
binary period, lacking binary phases $\phi_{98} = 0.30-0.39$. Sixteen nights of $BVR$ photometry were obtained from BO and 10 nights of $I$ photometry were obtained from RHO. Complete binary and spin phase coverage was obtained with all of the optical photometry. Blue and red spectra were obtained during two nights of observations, 2000 May 15 and 28 (UT), with the 3.5 m telescope at APO, which provided complete coverage of the binary and spin phases of EX Hya. The observations used the Double Imaging Spectrograph and obtained high-resolution (0.80 Å/pixel) blue spectra in the wavelength range 4185–5010 Å and high-resolution (1.17 Å/pixel) red spectra in the wavelength range 6285–7320 Å. These wavelength ranges include the H$\gamma$ λ4340.5, H$\beta$ λ4861.3, and H$\alpha$ λ6562.8 emission lines.

3. ANALYSIS

3.1. X-Ray and Optical Photometry

3.1.1. Period Analysis

We first searched for periods in each of our photometric data sets using the phase dispersion minimization (PDM) routine (Stellingwerf 1978), a technique for finding periods in a data set by minimizing scatter about a light curve. For a given input data set and range of test frequencies, PDM will compute a light curve and a binned light curve from the input data for each test frequency and the dispersion of the data about the mean light curve. The dispersion of the data will be at a minimum when a “real” frequency is found. This is reflected in the value of $\chi^2$ that PDM calculates. A two-sided $F$-test can then be used to calculate the confidence of a given frequency for which $\chi^2$ is at a minimum. The PDM results are shown as thetagrams in Figure 1 for the $B$, $I$, and RXTE photometry. Thetagrams were also created for the $V$ and $R$ photometric data but are similar to the $B$ plot in Figure 1 and are not presented here. Strong frequencies in the $B$ and $I$ thetagrams, above the 95% confidence level, include the spin frequency, $\omega$; the binary frequency, $\Omega$; harmonics of these two frequencies, $\omega/2$ and $2\omega$; and the beat frequencies, $\omega - \Omega$ and $\omega - 2\Omega$. They have been labeled on the RXTE and $B$ plots in Figure 1 and are listed in Table 2. The 99% confidence levels have been denoted on the plots as dotted lines. The frequencies shortward of $0.24$ day$^{-1}$ represent the length of the observations and also the time between data sets. The strongest frequency in each thetagram is $\omega$, with $\Theta = 0.76$ (RXTE), 0.42 ($B$), and 0.56 ($I$). Although several other frequencies appear above the 95% confidence level in the RXTE

| Instrument          | Observations$^a$ | Bandpass       |
|---------------------|------------------|----------------|
| Chandra             | 60 ks spectroscopy | 1–20 Å        |
| RXTE$^b*$           | 15 ks photometry and spectroscopy, 2000 May 18, 30 | 1–5 Å        |
| USA                 | 41.2 ks photometry | 1–10 Å        |
| EUVE                | 1000 ks photometry and spectroscopy | 70–180 Å     |
| FUSE                | 28 ks spectroscopy | 800–1200 Å    |
| HST                 | 6 orbits spectroscopy | 1100–1700 Å  |
| APO$^b*$            | 2 nights spectroscopy, 2000 May 15, 28 | 4200–5000, 6300–7300 Å |
| BO$^b*$             | 16 nights photometry, 2000 May 1–5, 7, 9, 10, 12–14, 25, 26 and Jun 2, 3, 7 | $B, V, R$    |
| RHO$^b*$            | 10 nights photometry, 2000 May 5, 8, 12, 18–20, 26–28, 31 | $I$          |
| UKIRT              | 1 night spectroscopy | 1.9–2.5 $\mu$m |

$^a$ Times given are in UT.
$^b$ Data presented in this paper.

Fig. 1.—Thetagrams for the $B$, $I$, and RXTE photometry. A smaller $\Theta$ value indicates a higher statistical confidence. (Note the y-axis has been inverted.) Frequencies commonly found in IPs are labeled on the $B$ and RXTE plots and listed in Table 2. The dotted lines represent the 99% confidence level, while the dashed line on the RXTE plot represents the 95% confidence level. The 99% confidence level for the $I$ thetagram is at 0.99. Values of $\Theta$ for the frequencies noted in this figure are given in Table 3.
the disk. We explore the appearance of the something has changed within the binary system that contributes to reprocessed light from the secondary and hot spot along with orbital absorption of emission from the white dwarf and reprocessed light from the inner accretion disk and accretion stream. The appearance of this frequency in our data set suggests that orbital absorption of emission from the white dwarf and reprocessed light from the secondary and hot spot along with orbital absorption of emission from the white dwarf and reprocessed light from the inner accretion disk and accretion stream.

Previous period analyses of X-ray photometry of EX Hya are limited. A search of the literature found only one instance: Allan et al. (1998) produced a power spectrum of their 40 ks ASCA observation (0.6–10.0 keV), which shows peaks at ω and Ω. Optical thetagrams are a bit more common, and a nice example can be found in Siegel et al. (1989), who report the appearance of the frequencies ω, Ω, Ω/2, and ω ± 2Ω. The appearance of ω − Ω is questionable in the Siegel et al. (1989) data set, and ω + Ω is not seen. While ω + Ω is also not seen in our data sets, ω − Ω is prominent. Emission at the beat frequency ω − Ω is due to reprocessed light from the secondary and hot spot along with orbital absorption of emission from the white dwarf and reprocessed light from the inner accretion disk and accretion stream. The appearance of this frequency in our data set suggests that something has changed within the binary system that contributes to emission and absorption at the ω − Ω beat frequency, which is most likely an extended hot spot region along the outer edge of the disk. We explore the appearance of the ω − Ω beat frequency further in § 3.2.1.

3.1.2. RXTE Photometry

Photometric data obtained from RXTE are shown in Figure 2 phased on the binary ephemeris, $T = 2437.6994179 + 0.068233846(4)E$, and spin ephemeris, $T = 2437.6998914(5) + 0.046546504(9)E − 7.9(4) \times 10^{-13}E^2$, (binned to 0.02 in phase) of Hellier & Sproats (1992). The binary-phased light curve, shown in the left panel of Figure 2, exhibits an eclipse at $\phi_{98} \sim 0.0$ of the X-ray-emitting region near the white dwarf surface.11 In addition to the binary eclipse, the light curve also displays quite a bit of variability throughout its entirety. This is a result of the combined effects of the X-ray flickering behavior of EX Hya and the poor phase coverage of the RXTE data. Each phase bin was covered only once or twice during the entire observation, in which case any flickering in individual cycles of EX Hya will not be averaged out. In particular, the flickering seen at $\phi_{98} \sim 0.65$

should not be confused with the bulge eclipse at $\phi_{98} \sim 0.7$ seen in lower energy X-ray data (<2 keV, e.g., Cordova et al. 1985; Rosen et al. 1988).

The binary-phased light curve has had the sinusoidal modulation subtracted. On an absolute count rate scale, it can be seen that the binary eclipse does not go to zero, implying a partial eclipse of the X-ray-emitting regions. This is a result of the lower accreting pole being eclipsed by the secondary, while the upper pole remains in view. Unfortunately, our RXTE data set is not extensive enough to analyze binary light curves extracted at different phase segments of the spin period.

In creating the spin-phased light curve, shown in the right panel of Figure 2, we omitted data from binary phases $\phi_{98} = 0.95–1.01$, which correspond to the binary eclipse. The X-ray flickering present in the binary-phased light curve is also seen throughout the spin-phased light curve. Ignoring this flickering, one can see that the data folded over spin phase exhibit a roughly sinusoidal modulation, peaking at $\phi_{67} \sim 0$, which is the signature of a rotating white dwarf accreting at both magnetic poles. The sinusoidal fit to the spin-phased data was created omitting the dip at $\phi_{67} \sim 0.8$; the solution of the form $A + B \sin(\phi_{67} - \phi_0)$ is given in Table 4.

3.1.3. Optical Photometry

Figure 3 displays the optical photometry of EX Hya folded on the spin ephemeris and binned to 0.02 in phase. Marked on the figure are the spin phase designations of maximum ($\phi_{67} = 0.99–1.24$), minimum ($\phi_{67} = 1.49–1.74$), rise ($\phi_{67} = 0.74–0.99$), and decline ($\phi_{67} = 1.24–1.49$), which are used for the analysis of the photometry folded on the binary orbital period. Data from the binary eclipse, $\phi_{98} = 0.95–1.01$, have been omitted in the spin-phased light curves. The BVR light curves are modulated sinusoidally [solutions for the sinusoidal fits of the form $A + B \sin 2\pi(\phi_{67} - \phi_0)$ are given in Table 4] and peak at $\phi_{67} = 0.12 ± 0.02$. The I light curve contains quite a bit of "wiggle," which is a result of modulations over the binary orbital period translating into the spin phasing. We do not believe that any of the I modulation is due to the secondary star. The optical spectra (out to 7200 Å, as well as an infrared spectrum obtained by one of us (S. B. H.) during the campaign, do not reveal any spectral features that could be associated with the secondary.

The maximum phase of $\phi_{67} = 0.12$ of the spin-phased light curves matches well with the value of $\phi_{67} = 0.115 ± 0.001$ determined from our EUVE photometry (Belle et al. 2002) but differs from the value of $\phi_{67} = 0.0$ obtained using the UV continuum flux from our HST data (Belle et al. 2003) and from the value of $\phi_{67} \sim 0$ we determine in this paper for the X-ray photometry. The discrepancy between the phases of spin maximum is addressed in § 4.

| Observed Frequency | Frequency (day$^{-1}$) | Period (minutes) |
|--------------------|------------------------|-----------------|
| $\omega$           | 20.48                  | 67.03           |
| $\omega/2$         | 14.74                  | 134.05          |
| $\Omega$           | 14.66                  | 98.26           |
| $\Omega/2$         | 7.33                   | 196.51          |
| $\omega − \Omega$  | 6.83                   | 210.88          |
| $\omega − 2\Omega$ | 7.83                   | 183.98          |

11 The sinusoidal form of the $O − C$ values given in Hellier & Sproats (1992) gives $O − C = −0.005P_{\text{orb}}$ for the 2000 May–June observations. Given the moderate time resolution of our data as presented, this shift in phase will be unnoticeable.

| Frequency | $\Theta^a$ |
|-----------|------------|
| $\omega$  | 0.42       |
| $\Omega$  | 0.92       |
| $\omega − \Omega$ | 0.55 |
| $\omega − 2\Omega$ | 0.59 |

$^a$ The 95% confidence levels are at $\Theta = 0.97$ (B), >0.99 (I), and 0.96 (X-ray); the 99% confidence levels are at $\Theta = 0.95$ (B), >0.99 (I), and 0.93 (X-ray).
Figure 2.—The RXTE photometry phased on the binary and spin ephemerides. The left panel shows binary-phased data after subtraction of the spin modulation. The solution for the sine curve shown fit to the spin-phased data in the right panel is given in Table 4.

Figure 4 displays representative light curves of the optical photometry folded on the binary ephemeris. The left panel of Figure 4 shows the $B$ binary-phased light curve after the sinusoidal spin modulation has been subtracted. The right panel of Figure 4 shows the $B$ data separated into spin maximum (top) and spin minimum (bottom). Each light curve has been binned to 0.02 in phase. The light curves exhibit typical behavior of an eclipsing binary system, with an eclipse near phase $\phi_{98} = 0.0$. This eclipse has typically been associated with an occultation of (part of) the white dwarf by the secondary star. Recently, however, it was questioned if this was a white dwarf eclipse, since the binary eclipse in EUV data of EX Hya appears at $\phi_{98} = 0.97$ (Belle et al. 2002); it was suggested that the optical eclipse was that of the hot spot on the outer edge of the accretion disk. Eclipse timings by Siegel et al. (1989) show that the eclipse minimum shifts between spin phases $\phi_{67} \sim 0.25$ and $\sim 0.75$ by about 20 s. Assuming a binary separation of $a \simeq 5 \times 10^{10}$ cm, they determine that the shift in eclipse minimum corresponds to an eclipse of material located (roughly) on the white dwarf surface. While our data do not have the high time resolution required to perform a detailed analysis such as this, close inspection of the unbinned light curves shows that the binary eclipse during $\phi_{67} \sim 0.75$ (rise) occurs ahead of the binary eclipse during $\phi_{67} \sim 0.25$ (decline) by $\sim 20$ s, consistent with the earlier results of Siegel et al. (1989).

The spin-separated light curves shown in the right panel of Figure 4 reveal additional information about the binary system. Inspection of the binary eclipse shows an extended egress shoulder on the spin minimum eclipse. This behavior is also seen in $V$, $R$, and $I$. This shoulder should be caused by an extended object (as compared with the white dwarf) coming out of eclipse, such as the bulge along the outer edge of the accretion disk, or as we discuss later, a region at the inner accretion disk radius where an overflow stream impacts with the magnetosphere. (Such a geometry would be favored during spin minimum.) A similar feature in the binary eclipse has also been reported by Hellier et al. (2000) for EX Hya during outburst.

### 3.2. Optical Spectroscopy

APO spectra from 2000 May 28 are shown in Figures 5 and 6. Figure 5 presents the mean blue and red spectra, which contain strong Balmer emission lines, as well as He I and He II emission. Figure 6 presents velocity line profiles of the H$\gamma$, H$\beta$, and H$\alpha$ emission lines plotted over the binary orbital period. The lines exhibit a double-peaked shape over all binary phases, indicative of emission from an accretion disk, and have average FWHM values of $\sim 50$ Å, or $\sim 2000$–$3000$ km s$^{-1}$.

#### 3.2.1. The s-Wave Component

The s-wave component of the emission lines, contributed by the hot spot on the outer edge of the accretion disk, is clearly visible as a redshifted or blueshifted component in the H$\alpha$, H$\beta$, and H$\gamma$ emission lines throughout most binary phases. The exact

### Table 4

**Sinusoidal Fits to the Spin-phased Photometry**

| Bandpass | $A^*$ | $B^*$ | $\phi_0$ |
|----------|-------|-------|---------|
| $B$ ...... | $-0.75 \pm 0.01$ | $-0.20 \pm 0.01$ | $0.87 \pm 0.02$ |
| $V$ ...... | $-0.27 \pm 0.01$ | $-0.17 \pm 0.01$ | $0.87 \pm 0.02$ |
| $R$ ...... | $-0.13 \pm 0.01$ | $-0.17 \pm 0.01$ | $0.87 \pm 0.02$ |
| $I$ ...... | $0.02 \pm 0.01$ | $0.13 \pm 0.01$ | $0.82 \pm 0.02$ |
| X-ray .... | $10.29 \pm 0.01$ | $1.09 \pm 0.15$ | $0.74 \pm 0.02$ |

* $A$ and $B$ have units of $\Delta m$ for $BVRI$ and counts s$^{-1}$ PCU$^{-1}$ for X-ray.

### Figure 3

The $BVRI$ optical photometry folded on the spin period. A sinusoidal function is fit to each light curve; solutions are given in Table 4. Phase delineations are given for spin maximum ($\phi_{67} = 0.99$–$1.24$), minimum ($\phi_{67} = 1.49$–$1.74$), rise ($\phi_{67} = 0.74$–$0.99$), and decline ($\phi_{67} = 1.24$–$1.49$). The offsets between the light curves are real magnitude differences.
behavior of the s-wave component varies between the emission lines. In H$\alpha$, the s-wave is redshifted during the early binary phases of $\phi_{98} = 0.03$–0.38 and has strongest zero-velocity emission during $\phi_{98} = 0.4$–0.5, the phases during which we are afforded a view of the hot spot on the opposite side of the accretion disk. The s-wave component is blueshifted from $\phi_{98} = 0.51$–0.60, is missing (or at least much less prominent) from $\phi_{98} = 0.64$–0.85, the phases during which we would expect to see the hot spot directly on the near edge of the disk, and is redshifted again at $\phi_{98} = 0.90$–0.99.

In the H$\beta$ and H$\gamma$ emission lines, the s-wave component follows the general behavior of that seen in the H$\alpha$ line, with a few exceptions. The s-wave component is at zero velocity at $\phi_{98} \approx 0$ and $\sim 0.3$, where the H$\alpha$ s-wave component is redshifted. It also becomes blueshifted at earlier phases, around $\phi_{98} \approx 0.4$ for both the H$\beta$ and H$\gamma$ lines, while it is still at zero velocity in the H$\alpha$ line. The s-wave component also appears to bounce back and forth between red- and blueshifted during binary phases $\phi_{98} = 0.60$–0.85. Another intriguing feature of the H$\gamma$ and H$\beta$ emission lines during these phases is that there is little to no zero-velocity emission.

Taking the general behavior of the s-wave component from all three lines, we can infer geometric properties of the hot spot and bulge on the outer edge of the accretion disk. The s-wave component is redshifted from $\phi_{98} \sim 0.85$–0.3, at zero velocity around $\phi_{98} \sim 0.3$–0.4, and is blueshifted from $\phi_{98} \sim 0.4$–0.6. After $\phi_{98} \approx 0.6$, the s-wave component disappears. The zero-velocity emission phase at $\phi_{98} \sim 0.3$–0.4 tells us that the s-wave component is dominated by emission on the opposite side of the disk, between phases $\phi_{98} \sim 0.8$–0.9 on the accretion disk. This emission therefore appears as a redshifted component from $\phi_{98} \sim 0.85$–0.3. The s-wave is only blueshifted when this component moves toward the observer, during phases $\phi_{98} = 0.4$–0.6. At phase $\phi_{98} = 0.6$, material begins to obscure our view of the hotter parts of the hot spot, and so the s-wave component disappears. From the missing s-wave emission during phases $\phi_{98} = 0.60$–0.85 and the absence of any zero-velocity component in the emission lines, we can infer that there is vertically extended material along the outer edge of the disk obscuring the s-wave and zero-velocity components starting at $\phi_{98} \sim 0.6$. This extended material is likely irradiated along its inner edge by the white dwarf and gives rise to the s-wave emission.

Further evidence for extended emission along the outer edge of the disk is seen in the Doppler tomogram for the H$\alpha$ emission line, displayed in Figure 7. The binary phase tomograms shown in the figure are measured from spectra obtained on 2000 May 28. The H$\alpha$ tomogram shows enhanced emission along the outer edge of the accretion disk, for approximately 0.5 in phase. Extended emission along the outer edge of the accretion disk is also indirectly observed in the EUV data of EX Hya, in the form of absorption of the EUV-emitting region (Belle et al. 2002). This absorption also lasts for approximately half of an orbital phase.

Each tomogram exhibits a bright area of emission at $\phi_{98} \sim 0.8$; this is the hot spot and is the origin of the s-wave component. The H$\gamma$ and H$\beta$ tomograms also show enhanced emission that appears to extend from the region at $\phi_{98} \sim 0.8$ toward the inner regions of the disk ($R_{\text{in}} \lesssim 6.5R_{\text{WD}}$, see § 3.2.2). Hellier et al. (2000) observed evidence of disk overflow in EX Hya during its 1998 outburst. In X-rays, the overflow stream was indirectly observed as an $\omega$–$\Omega$ beat modulation, and in the optical, the overflow stream was detected via its eclipse and from line emission at the site of the stream impact with the magnetosphere. We checked AAVSO data of EX Hya for the time period immediately preceding and following our observations, but the available data show no evidence of an outburst. In fact, the data points for EX Hya show it sitting at 13–12.5 mag, which is its normal quiescent brightness. This would rule out a period of enhanced mass transfer as the cause of the overflowing material inferred from our data, as such an event would likely be indicated by an increase of the system brightness.
Tomograms plotted over the white dwarf spin phase were also constructed; however, these show no coherent emission sites. It has also been shown previously (Hellier 1999) that tomograms of EX Hya folded on the spin phase reveal little information.

### 3.2.2. Radial Velocities

Measuring the central wavelengths of the H emission lines proved to be a challenge, since the double-peaked nature of the lines and the contribution of the s-wave component made it difficult to use a single Gaussian profile for determining line parameters. We therefore used a method for fitting a double-Gaussian profile to the emission lines, which measures radial velocities from emission-line wings (D. W. Hoard 2004, private communication; for a description of double-Gaussian fitting see Shafter 1983; Shafter et al. 1986).

We created radial velocity curves for the Hγ, Hβ, and Hα emission lines. Figure 8 displays the radial velocity curves for the Hα and Hβ lines. Strong asymmetries due to emission from the hot spot prevented accurate determinations of $K_1$ or $\gamma$ from fitted sine curves, but a fit of the form $v = \gamma + K_1 \sin 2\pi(\phi - \phi_0)$ to the Hα line (shown in Fig. 8) gives $\gamma = -14 \pm 1$ km s$^{-1}$, $K_1 = 61 \pm 6$ km s$^{-1}$, and $\phi_0 = 0.115 \pm 0.016$. The $K_1$ value of 61 km s$^{-1}$ is in agreement with our previous value of $K_1 = 59.6 \pm 2.9$ km s$^{-1}$ determined from narrow UV emission lines (Belle et al. 2003) but slightly lower than a previous value of 69 km s$^{-1}$ determined from optical emission lines by Hellier et al. (1987).

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**Fig. 6.**—Hγ, Hβ, and Hα velocity line profiles shown over the binary orbital period (phase noted in the upper right corner of each plot) for data from 2000 May 28. The s-wave component is clearly visible as a red- or blueshifted component during most binary phases. The Hβ and Hα line profiles have been shifted upward in flux by 0.5 and 1.0, respectively.

**Fig. 7.**—From left to right, tomograms over the binary phase for the Hγ, Hβ, and Hα emission lines from spectra obtained during the night of 2000 May 28. Each tomogram shows a bright spot at $\phi_0 = 0.8$. The Hγ and Hβ tomograms show enhanced emission from the hot spot toward the inner edge of the disk. Extended emission (roughly half of the orbital phase) is seen along the outer edge of the accretion disk in the Hα tomogram. The phasing of the tomograms follows standard convention, in which binary phase 0 is at 12 o’clock on the plot and phase increases clockwise.
We also calculated the radial velocity of the s-wave component in each of the H\β emission lines. We found that the velocity amplitude of the s-wave emission places the emission site at $9 \times 10^{16}$ cm from the center of the white dwarf for the H\α component and at $3 \times 10^{16}$ cm from the center of the white dwarf for the H\β and H\γ components. The smaller value obtained from the H\β and H\γ radial velocities may be due to contamination from the overflowing material. If we assume that the s-wave component originates at the outer edge of the accretion disk, the placement of the H\α s-wave component gives an outer disk radius of $R_{\text{out}} \approx 10^{15}$ cm. The inner accretion disk radius may be measured from the high-velocity emission-line wings, which extend at least to 1500 km s$^{-1}$ (Fig. 6). This velocity gives an upper limit to the inner disk radius of $R_{\text{in}} = 6.5R_{\text{WD}} = 5 \times 10^{10}$ cm for a 0.8 $M_{\odot}$ white dwarf or $R_{\text{in}} = 2.9R_{\text{WD}} = 3 \times 10^{10}$ cm for a 0.5 $M_{\odot}$ white dwarf.

4. COMPARISON OF DATA AT ALL WAVELENGTHS

A comparison of data from all wavelength regimes can lead us to an overall picture of EX Hya. Signatures of an extended bulge along the outer edge of the accretion disk are seen in the EUV photometry as absorption of the EUV-emitting region on the white dwarf surface, in the optical spectroscopy as enhanced emission in the H\β emission-line tomogram, and as absorption of the zero-velocity components of the H\β and H\γ emission lines during certain binary phases. The absorption at phases $\phi_{98} = 0.55 - 1.1$ in the EUV photometry match well with the absorption in the H\β and H\γ emission lines, seen at $\phi_{98} = 0.6 - 0.9$. The fact that the bulge is not present as a source of continuum emission in the binary-phased light curves implies that the bulge material is optically thin.

Some form of overflowing material is seen in the Doppler tomograms of the H\β and H\β emission lines as enhanced emission extending from the hot spot toward the inner edge of the accretion disk. Other evidence for overflowing material comes from the blueshifted velocities of the Balmer lines at $\phi_{98} \approx 0.4$. One may also infer the existence of an extended/overflowing hot spot from the extended egress shoulder of the binary eclipse during spin minimum phases, which implies that an additional source, other than the white dwarf, is coming out of eclipse.

Some inconsistencies remain. The first is the phase of spin maximum as derived from light curves of continuum and emission-line fluxes. X-ray spin maximum occurs at $\phi_{97} \approx 0$, EUV at $\phi_{97} = 0.115 \pm 0.001$, UV continuum at $\phi_{97} = 0.01 \pm 0.05$, UV emission lines at $\phi_{97} = (0.05 - 0.08) \pm 0.05$, and optical at $\phi_{97} = 0.12 \pm 0.02$. The difference in the phase of spin maximum has been reported previously by Hellier et al. (2000) for their simultaneous X-ray and optical observations. An extended accretion region on the white dwarf surface would be an initial suggestion for the difference in phase of spin maximum; however, one would expect that the high-energy spin maxima would be coincident, but this is not the case.

Another inconsistency is the phase of the binary eclipse across wavelength regimes. X-ray and optical data show the binary eclipse at $\phi_{98} \approx 0$, while EUV data display two eclipses near, but not at, $\phi_{98} = 0$: one at $\phi_{98} = 0.97$ and the other at $\phi_{98} = 1.04$. The EUV eclipse at $\phi_{98} = 1.04$ could be an eclipse of the disk overflow stream impact with the magnetosphere, although this region would not be expected to be bright in the EUV. However, there still remains the phase difference of the binary eclipse. The difference between the EUV and X-ray eclipses could be reconciled by the fact that the RXTE coverage of those phase bins is not nearly as extensive as the EUVE coverage. Perhaps observations that provide better phase sampling would show the X-ray eclipse slightly earlier in phase. In such a case, then, a physical displacement between the higher and lower energy emitting regions could be the cause of the phase difference of the binary eclipses.

5. CONCLUSIONS

We have presented simultaneous X-ray and optical photometry and optical spectroscopy of the IP EX Hya obtained as part of a large multiwavelength observational campaign of EX Hya. The data provide evidence for an extended bulge along the outer edge of the accretion disk, corroborating our EUV results (Belle et al. 2002). Over the binary orbital period, the zero-velocity component of the optical emission lines is seen to be absorbed during binary phases $\phi_{98} = 0.6 - 0.85$. The H\α tomogram also shows enhanced emission along the outer edge of the accretion disk at phases $\phi_{98} = 0.6 - 0.85$. The H\β and H\γ tomograms also indicate that some amount of material may be extended from the hot spot toward the inner regions of the accretion disk.

Combined together, the data suggest that EX Hya may be experiencing a period of enhanced mass transfer, as the data presented here bear similarities to the outburst data of 1998. The system remained, however, at its quiescent brightness of $\sim 13$ mag during the observations. Perhaps there was a period of enhanced mass transfer that was not recorded, or EX Hya may not have returned entirely to its quiescent state after outburst. Finally, we would like to call the attention of the reader to an initial light curve of EX Hya published by Mumford (1967, Fig. 5) prior to knowledge of EX Hya as an IP (i.e., no spin modulation was subtracted from the light curve). This light curve (which has $\Delta m \approx 0.4$ between eclipses) shows none of the modulation associated with the white dwarf spin period that is so prevalent in our 2000 photometric data ($\Delta m \approx 0.7$ between eclipses). Obviously, conditions within EX Hya, e.g., a larger bulge or extended accretion curtains, have changed in order to produce the enhanced emission. It is apparent that obtaining over one million seconds of data has only increased the number of questions we have about EX Hya.

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