SIMULTANEOUS EXTREME-ULTRAVIOLET AND INFRARED OBSERVATIONS OF THE ECLIPSING POLAR HU AQUARII

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ABSTRACT

We present simultaneous EUV and infrared (J, K) observations of the polar HU Aquarii obtained during 1998 August when the star was in a high mass accretion state. EUV and IR light curves and EUV spectra are presented and compared with previous observations. The accretion region on the white dwarf has increased in temperature (124,000 to 240,000 K) and radius (0.04R WD to 0.06R WD) compared with previous EUV observations made during low mass accretion states. The EUV and IR photometric observations are shown to have a similar appearance as a function of orbital phase. The EUV photometry shows rapid changes and provides evidence for mass accretion via blobs. The high-state IR light curves present an asymmetric double-humped shape with \( J = 14.8 \) and \( K = 14.1 \). We applied an ellipsoidal model fit to the observations, and the result indicates that the cause of the modulated shape is due to both ellipsoidal variations from the Roche lobe filling secondary star and a complex flux combination probably dominated at all orbital phases by cyclotron emission. The source of maximum cyclotron emission appears to be in the accretion column high above the white dwarf surface.

Key words: binaries: eclipsing — binaries: general — novae, cataclysmic variables — stars: individual (HU Aquarii) — stars: magnetic fields

1. INTRODUCTION

HU Aquarii (RX J2107.9 – 0518) is a member of the polar or AM Herculis type of cataclysmic variable. Polars consist of an interacting pair of stars (white dwarf plus red dwarf) in which the white dwarf primary is strongly magnetic. The material accreted from the low-mass secondary is magnetically controlled over the final portion of its flow being forced to funnel along the field lines and impact directly onto the white dwarf surface. The general location of the material impact site on the white dwarf surface is termed the accretion region. HU Aqr has an orbital period of 2.08 hr, and the white dwarf magnetic field strength is estimated to be 36 MG.

High-energy observations of polars provide us with direct information related to the accretion regions near the white dwarf surface surrounding the magnetic poles (see Sirk & Howell 1998; Schwope et al. 2001a). A number of high-energy observations have been obtained for HU Aqr because of both its brightness at X-ray and EUV wavelengths and the fact that it is an eclipsing system. Eclipsing systems allow absolute orbital phase information to be obtained without ambiguity caused by accretion stream or accretion region eclipses. Phase-dependent phenomena are then able to be referenced to an unchanging fiducial. A review of the observational history of HU Aqr, in particular the high-energy observations, is provided by Schwope et al. (2001a).

Infrared observations of cataclysmic variables are useful as a tool to understand the secondary star, which is typically of late spectral type and bright in the IR. These parameters are addressed through observations of ellipsoidal variations and the secondary-star spectral energy distribution. IR observations also provide information about the cooler areas of the accretion stream and cyclotron radiation produced in the hot regions near the accretion spot. The usefulness of IR photometry is illustrated in Ciardi et al. (1998) and Howell, Gelino, & Harrison (2001) and IR spectroscopy in Howell et al. (2000).

In this paper, we present simultaneous EUV and infrared observations for HU Aqr obtained during a high mass accretion state in 1998 August. The EUV observations allow us to measure the size and location of the accretion region and its temperature, while IR photometry presents contributions from the accretion stream and cyclotron radiation. The only previous attempt at such a multiwavelength simultaneous approach was by Watson et al. (1989) using EXOSAT X-ray, optical, and IR data for the polar EF Eri. These authors concluded that the coincident dips seen in all the bands were caused by absorption in the accretion stream as it crosses the line of site to the accretion pole. Our new data allow a more detailed understanding of the process, and we find that the two apparently distinct wavelength bands seem to have previously undiscovered commonalities, since we find a correlation in their phase-resolved flux distributions.

2. OBSERVATIONS

2.1. EUV Observations

The Extreme Ultraviolet Explorer (EUV) satellite performed simultaneous spectroscopic and photometric observations in the EUV spectral range (Bowyer & Malina 1991). The principle instrument on board consists of a telescope that contains an imager and three separate spectrographs.
covering the range of 70–750 Å. The bandpass of the deep survey imager is set by the Lexan/boron filter, with a maximum transmission at 91 Å with a 90% bandpass of 67–178 Å. The imager allows for collection of photometric data simultaneously with the spectroscopic data. The EUVE obtains short-wavelength, medium-wavelength, and long-wavelength data as three separately imaged dispersions covering the ranges of 70–170, 150–350, and 300–700 Å, respectively. All collected photons are position and time tagged providing high time resolution and allowing the production of detailed light curves (see, e.g., Sirk & Howell 1998) and spectra (see, e.g., Craig et al. 1997; Mauche 1999; Howell et al. 1997). Details of the photometric properties of the imaging telescopes on board the EUVE may be found in Sirk et al. (1997), and the spectroscopic instruments are reviewed in Abbott et al. (1996).

The EUVE observations of HU Aqr were obtained during the time period 1998 August 27 (21:47:10.0 GMT) to 1998 August 29 (21:30:49.0 GMT) with a total on-source integration time of 65.432 ks. This time coverage contained 8.7 consecutive orbital periods of HU Aqr. During the EUVE observation, HU Aqr was detected with a mean count rate of 0.8 counts s\(^{-1}\) photometrically and \(\sim 0.1\) counts s\(^{-1}\) (near 100 Å) spectroscopically. No EUV flux was detected longward of \(\sim 110\) Å because of absorption by the interstellar medium (ISM). The high count rate observed made HU Aqr approximately 15 times brighter than any previous observation made with EUVE (see below), which spanned the time period of 1996–1997. The EUVE spectral data were extracted and reduced to phased-resolved two-dimensional images as described in the EUVE users manual, and then to one-dimensional spectra as discussed in Hurwitz et al. (1997). The photometric data reduction proceeded as described in Howell et al. (1995).

Figure 1 presents the mean EUV light curve obtained during the 1998 August observation binned in 15 s intervals. Various phases of interest, which will be used later on, are identified on the figure, and we note that the eclipse egress lasts less than 2 s. All data in this paper are phased on the ephemeris of Schwoppe et al. (1998).

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T(\text{HJD}) = 2,449,217.345162(27) + 0.08682041520(82)N,
\]

with phase 0.0 representing the time of inferior conjunction of the secondary star. This ephemeris is equivalent to that of Schwoppe et al. (2001a) to within 10\(^{-4}\) s.

The previous observations of HU Aqr made with EUVE had too low of a count rate for useful spectra to be extracted. With the higher flux present in the current data set, we are able to produce not only a summed spectrum covering the entire on-source time, but single spectra from phases of interest within the orbital cycle. Figure 2 shows our results for HU Aqr, labeled as to their phases as marked in Figure 1 and binned to a final spectral resolution of 0.8 Å. The spectra shown in Figure 2 have been corrected for EUVE dead time, Primbsching, and the spectrograph effective area response function (see Abbott et al. 1996).

### 2.2. Infrared Observations

Using the 2.34 m infrared telescope at the Wyoming Infrared Observatory near Woods Landing, Wyoming, HU Aqr was observed on UT 1998 August 29 and 30 in the near-infrared broadband filters \(J\) and \(K\) using the Aerospace Corporation 256 \(\times\) 256 NICMOS3 camera. The camera has a spatial resolution of 0\('\)43 pixel\(^{-1}\) for a total field of view of 110\('\) \(\times\) 110\('\). The array has a quantum efficiency of \(\geq 60\%\) over the 1–2 \(\mu\)m wavelength range, an approximate dark current of \(\lesssim 1\) e\(^{-}\) s\(^{-1}\), and a readout noise of \(\lesssim 30\) e\(^{-}\) pixel\(^{-1}\).
To minimize the effects of a variable sky background, the data were acquired in image “nod pairs.” A nod pair consists of a “plus beam” image and a “minus beam” image, which are spatially separated from each other by 20′′ in declination. The integration time of a single frame within a nod pair was 20 s. The image collection was performed such that a pair of images (one per “beam”) was taken before changing filters. The images for the nod pair are thus very close in time, ∼11 s, which incorporates the readout and writing to disk of the first image and the slewing of the telescope by 20′′ (including settling time). The nod of the telescope was chosen carefully so that the source and two non-variable comparison stars remained within the field of view for both beams. After each filter-nod sequence, the filter was changed and the sequence repeated. Successive filter pairs are separated by ∼2.5 minutes.

To increase the signal-to-noise ratio (S/N) of the photometry, images within a nod pair were registered and co-added, and standard differential photometry was performed on each co-added image as described in Howell, Mitchell, & Warnock (1988). Absolute photometry was obtained by observing a near-infrared standard star from the list of Elias et al. (1982) just prior to the start of the HU Aqr observations. The HU Aqr observations for the two nights were combined and phased on the orbital period using the same ephemeris as the EUVE data. The final J and K light curves are shown in Figure 3, where they are compared with the 1996 J and K light curves from Ciardi et al. (1998). HU Aqr had mean J and K magnitudes of 16 and 15, respectively, in 1996, while our new 1998 measurements have mean J and K magnitudes of 14.8 and 14.1, respectively.

3. RESULTS

3.1. EUV

Figure 4 presents all the EUVE observations of HU Aqr. The 1998 August observation (bottom) has a much greater count rate than any of the other light curves in Figure 4, and its shape has dramatically changed. The time sequence seen in Figure 4 prior to the 1998 observation was originally thought to represent a progression of HU Aqr into a low mass accretion state. However, the 1998 observation would seem to indicate that all the previous EUVE observations were during a low mass accretion state, some just lower than others. Perhaps the most dramatic change observed in the 1998 EUV photometry of HU Aqr is the fact that the post-eclipse flux is now greater than the pre-eclipse flux, the opposite behavior to essentially all the low mass accretion state observations (Fig. 4). ROSAT observations of HU Aqr made in 1993 show similar count rate ratios compared
with the 1998 August EUVE observation and also have higher post-eclipse fluxes (see Fig. 2 in Schwope et al. 2001a).

Many EUVE and ROSAT observations contain no flux from phase 0.9 to 0.97. The reason for this lack of flux is probably due to the accretion curtain blocking our view of the accretion region during this phase interval (see Sirk & Howell 1998; Schwope et al. 2001a). Additionally, we will see below that the flux level within the 0.9–0.97 phase window can be highly time variable.

Fig. 5.—Eight consecutive binary orbits of HU Aqr from the 1998 EUVE observation. Each light curve consists of ~7400 s of data (~1 binary orbit) composed of four consecutive EUVE satellite orbits and phased on the binary ephemeris. The data are summed in 20 s bins. The top of each plot gives the start time for each light curve. Note the rapid changes that occur in each 2 hr time interval, especially near phases 0.7–0.9.
Figure 5 presents eight consecutive EUV HU Aqr light curves obtained during the 1998 August observation. Each of the eight panels spans about a quarter-day or three binary orbits of HU Aqr. The dotted line in Figure 5 is the mean light curve of Figure 1 illustrating that changes from orbit to orbit clearly exist. Note, for example, the change in flux near phase 0.25 related to effects in the far-field accretion stream and the accretion curtain (near field stream) and the fast changes in absorption near phase 0.75 due to the near-field accretion column. Sirk & Howell (1998) and Schwope et al. (2001a) show that changes in the shape of the soft X-ray/EUV light curves occur from observation to observation (months to years apart), and these changes provide evidence for the movement of the accretion stream due to changes in the mass accretion rate. Figure 5 provides evidence that rapid (few hour) changes occur during this high mass accretion state and are probably related to local opacity variations or blobs within the accretion stream and column (see § 4).

Figure 6 shows our 1998 August spectrum during the bright phase (bottom) compared with the spectral sum of three previous observations (made during 1996) co-added over all phases with nonzero EUV flux. The final binned spectral resolution is 0.54 Å for both plots in Figure 6. While the older summed spectrum is of lower S/N, it is clear from its appearance that it is produced by a cooler accretion region than that in the 1998 August observations (see below).

3.2. Infrared

Infrared J and K light curves from 1998 and 1996 are shown in Figure 3. A comparison of the light curves from the two epochs reveals some intriguing features. The most striking difference between the light curves is that the 1998 data are, on average, 2.5–3 times brighter than 1996 data. The infrared brightness increase is ~15 times lower than the EUVE brightness increase.

At first glance, the 1998 and the 1996 light curves appear to be similar in structure. Both sets of light curves display the deep stellar eclipse bottoming out at J ~ 16.4 mag and K ~ 15.4 mag. While the overall infrared brightness has increased between 1996 and 1998, the depth of the eclipse has not changed, indicating that the infrared eclipses are total, and the bottom of eclipse is representative of the back of the secondary star (see Ciardi et al. 1998).

In addition to the deep stellar eclipse, both J and K light curves are double humped. The 1996 observations show two symmetric humps centered at orbital phases 0.25 and 0.75, which are well fitted with an ellipsoidal variation model of the secondary stellar photosphere. The ellipsoidal model from Ciardi et al. (1998) is shown in Figure 3 and is over-plotted upon the 1996 and 1998 data. The model, which explains the global variation of the 1996 data, does not explain the variations observed in the 1998 data. The 1998 “humps” are out of phase with those expected for ellipsoidal variations and are not symmetric in shape or amplitude. The ellipsoidal variations of the secondary star probably did not disappear between 1996 and 1998 (see Howell et al. 2000), but rather during this high accretion state, the secondary-star flux is now overpowered by orbitally modulated variations from another source. We note here a general warning to observers of polars that infrared light curves with “double-humped” structures do not necessarily constitute ellipsoidal variations of the secondary star. This same misconception has been seen in the optical as well (Howell et al. 2001). Thus, while ellipsoidal variations may still effect the light-curve shape by providing some amount of the modulated structure, we will see below that the IR light curve in HU Aqr is quite complex and dominated by another source.

4. DISCUSSION

4.1. EUV: Light Curves and Spectra

Sirk & Howell (1998) developed a three-dimensional model that allowed EUV photometric data to be fitted in terms of various parameters dealing with the size, shape, and location of the accretion region on the white dwarf surface. Table 1 summarizes the findings from their original work on the 1996 EUVE observations of HU Aqr along with our new values determined from model fits to the current data. It has been assumed that the orbital period of HU Aqr has remained constant, and we have used the new determination of the system inclination, 85°6 (Schwope et al. 2001a), instead of the value of 81° available to Sirk & Howell. Schwope et al. (2001a) determined the size of the accretion region in HU Aqr for the high-state 1993 ROSAT PSPC observations by analyzing eclipse ingress timings and by applying the three-dimensional Sirk & Howell model. In
both cases, they found a consistent size of \(0.052R_{\text{WD}}\) (1 \(\sigma = 0.02\)). This value is essentially the same as our high-state determination listed in Table 1. In addition, there are enough photons to examine eclipse egress in the 1998 observations, and its duration of 1.5–2.0 s sets an upper limit on the EUV-emitting region of 0.07\(R_{\text{WD}}\). Our Table 1 values for the 1996 and 1998 spot heights are the same, but they are larger than the value of 0.014\(R_{\text{WD}}\) given in Schwope et al. No uncertainty is given for the value of the height determined by these authors, but if it is similar to our uncertainty (\(\pm 0.003\)), then we are not too far apart in our calculated heights. We find that the accretion region in HU Aqr has increased its area by a factor of \(\sim 2.8\), if approximately spherical in cross section, during this high mass accretion state. Uncertainties in the accretion region modeling procedures are fully discussed in Sirk & Howell (1998).

The three large dips seen in the EUV light curve (Fig. 1) are due to local absorption of EUV flux by the near-field and far-field accretion columns caused by our line of sight through to the accretion region. Sirk & Howell (1998) found that a comparison of the EUV spectra obtained for UZ For, VV Pup, and AM Her during their broad dip phases with that observed during their bright phase (see their Fig. 9) led to the result that spectra observed during the broad dips were softer than those obtained during the (assumed) unoccluded bright phase. To see if this result holds for HU Aqr as well, we have taken the sum of our two HU Aqr “dip” spectra (dip 1 and dip 2; bottom two panels in Fig. 2) and compared them with the bright phase spectrum. The low S/N in the dip spectrum made the comparison rather noisy, but over the region of 70–90 Å, the spectrum appeared softer than that collected during the bright phase, exactly what was found for UZ For, AM Her, and VV Pup.

Sirk & Howell (1998) have shown that the broad dip is caused by material very close to the accretion region (the near-field stream) and modeled it with a cylindrically symmetric, uniformly dense absorber immediately above the accretion spot. Schwope et al. (2001a) show that it is not a cold absorber that is responsible for the broad dip. The broad dip in the EUV light curves of HU Aqr varies on short (binary period) timescales as can be seen in Figure 5. The large variations from orbit to orbit indicate that the broad dip is a changeable feature in both phase and shape: the “broad dip” shape becoming manifest only when many individual orbits are averaged together. Warren, Sirk, & Vallerga (1995) found a similar behavior in the polar UZ For.

The many ROSAT and EUVE data sets for HU Aqr were used to search for correlations between accretion rate, spot latitude, stream dip phase, and broad dip phase as a function of time. The results are presented in Table 3 in Schwope et al. (2001a). Most of the observations show the broad dip to occur at early orbital phases (\(\phi = 0.69–0.77\)), however, a third of the observations show no clearly defined broad dip at all. To graphically illustrate the changes in the broad dip in HU Aqr, we show a normalized average EUV light curve (dotted line) drawn on each of the individual light curves in Figure 4. This average curve was produced by taking every EUVE light curve of HU Aqr, normalizing each to its maximum value, averaging them all together, and then overplotting them (scaled by each light-curve maximum) on each single epoch light curve in Figure 4. Comparison of the “dipless” individual light curves in Figure 4 (1996 May, July, and September) with the normalized overplotted average light curve reveals a deficit of flux at later phases (around \(\phi = 1.0–1.1\)). An extreme example of this effect can be seen in the ROSAT HRI 1996 April observation (See Fig. 2 in Schwope et al. 2001a), where the second half of the light curve is nearly absent.

A quantitative correlation between the broad dip phase and the mass accretion rate is difficult to access, but the following appears to be true. At a high accretion rate, where we see the broad dip occur at an early phase, the low-density portion of the ballistic stream latches onto the magnetic field first and strikes the WD at a relatively low longitude, and the higher density portion of the stream (blobs) penetrate further into the magnetic field and land on the WD at a greater longitude. Our view to the accretion spot through the column will then be most obscured at early phases (i.e., causing a flux deficit).

For the broad dip to occur at an early phase, it requires absorbing material to lead the EUV accretion spot in longitude on the white dwarf surface. When at later phases, the material must lag in longitude. We conclude that the near-field accretion curtain is nonuniform in density at any given phase at any given time. Thus, at different times, we are looking through varying amounts of absorbing material, and these differences in column density are probably influ-

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**TABLE 1**

**ACCRETION REGION PARAMETERS FOR HU AQUARI**

| Parameter                     | 1996 May | 1998 August |
|-------------------------------|----------|-------------|
| Spot radius (\(R_{\text{WD}}\)) | 0.036    | 0.061 (5)   |
| Spot radius (10\(^6\) cm)    | 2.16     | 3.66        |
| Spot area (10\(^{15}\) cm\(^2\)) | 1.47     | 4.21        |
| Fractional emitting area      | \(3.27 \times 10^{-4}\) | \(9.36 \times 10^{-4}\) |
| Spot height (\(R_{\text{WD}}\)) | 0.021    | 0.023 (3)   |
| Spot latitude (deg)           | 34.5\(^e\) | 36.7        |
| Spot longitude (deg)          | 49       | 49 (1)      |
| Accretion region temperature (K) | \(~124,000\) | 240,000 (40,000) |

\(^a\) We assume here a white dwarf radius of 6000 km (Ciardi et al. 1998).

\(^b\) From Sirk & Howell 1998.

\(^c\) Numbers in parentheses are 1 \(\sigma\) errors.

\(^d\) This value was reported as 40\(^e\) in Sirk & Howell 1998, but using the new binary inclination estimate of 85\(^d\) (Schwope et al. 2001a), compared with the older value of 81\(^d\), we subtract 4\(^d\).
enced by how the ballistic stream attaches onto the magnetic field lines within the coupling region. Even small mass accretion rate changes or blobby accretion will supply varying ram pressure, causing the field lines to bend and changing the exact location of the coupling region for any given field line.

Mauche (1999) provided a detailed look at modeling the EUV spectra of polars. He concluded that absorbed blackbody models provide the best phenomenological description for the 70–180 Å spectra of polars. However, Mauche and prior work by Paerels, Heise, & van Teeseling (1994) both note problems with such a simple approach. The weak absorption edges and lines (mostly due to Ne species) are not properly dealt with, and blackbody fits are unable to produce the observed EUV fluxes. Use of an irradiated solar composition stellar atmosphere model is likely to be more proper, but models of this type need to be improved by adding in non-LTE effects, the underlying white dwarf, and absorption lines. Likewise, the quality of the spectral data to be modeled must greatly improve in order to allow quantitative analysis.

An additional complexity pointed out by Paerels et al. (1994) is the fact that a change in the fitted blackbody model continuum level will cause corresponding changes in the observed absorption-line strengths. The use of simple blackbody models (especially to fit a mean spectrum) forces a “best-fit continuum” criteria on the user, thereby fixing the apparent line strengths. Fluctuations in intensity and spectral distribution that occur over time and orbital phase are not accounted for. The S/N of the spectrum also plays a role here, since it influences the selection of the best fit. A detailed example is given in Paerels et al. Given the moderate S/N of our HU Aqr spectra and the fact that an absorption features superposed on a blackbody spectrum would be consistent with a two-temperature model for the high-energy emission from the accretion region, we can expect that the underestimation of the white dwarf atmosphere by the bremsstrahlung radiation (an irradiated atmosphere) at and near the accretion region. The lack of any visible O vi lines in the HU Aqr spectrum suggests that the white dwarf atmosphere is heated only to small depths near the accretion region (van Teeseling, Heise, & Paerels 1994; and see Fig. 1 in Paerels et al. 1996).

Using point sources (white dwarfs and B stars) observed with EUVE for the purpose of mapping out the ISM, we can estimate the interstellar column to HU Aqr. Ten sources in the EUVE data archive located in the direction of and near the distance of HU Aqr (125 pc; Ciardi et al. 1998) were used to provide an initial estimate for the column density to HU Aqr of \( \log N_H = 19.75 \) (assuming \( H = 0.1 \) and \( H = 0.1 \)). Starting with this column density estimate and allowing our blackbody temperature and \( \log N_H \) to be free parameters, we determined a best-fit absorbed blackbody solution for our summed spectrum (Fig. 6, bottom). Our best fit yields a temperature of 240,000 \( \pm 40,000 \) K (20.68 \( kT \) [eV]) for the accretion region with a column to HU Aqr of \( \log N_H = 19.48 \pm 0.32 \). These values are in excellent agreement with those determined by Schwpe et al. (2001a) for HU Aqr during a similar high mass accretion state ROSAT PSPC observation made in 1993 October. Attempts to fit absorbed blackbody models to the individual spectra from our 1998 August data or to the summed spectra from the 1996 data sets yielded large uncertainties because of their low counting statistics. The accretion region temperature for the 1996 low mass accretion state was found to be much cooler, with a best fit near \( \sim 124,000 \) K, based on the spectral slope and assuming that the column density remained constant.

Spectral lines or edge lines have been observed for a few polars in EUVE spectra (see a review by Mauche 1999). Mauche (1999) presents a detailed reanalysis of these same data and finds convincing evidence in a subset of the polars for lines due to Ne vi, Ne vii, and Ne viii. Our 1998 August HU Aqr summed spectrum reveals a few features that may be real atomic absorption lines and is of sufficient S/N to allow a qualitative examination of these possible spectral features. Searching the likely line species for polars present in the 70–100 Å range (N, O, Ne, Mg, and S), absorption lines due to Ne vii at 73.5, 76(7), and 98.2 Å are the only set of consistent and possibly believable features. Ne vi line edges at 78.5 and 85.2 Å and that for O vi at 89.8 Å may be present. Ne viii (98.2 Å) seems to be present in the 1996 low-state spectrum as well.

The ionization potential for Ne viii (239 eV) is too high to be provided by the EUV blackbody emission as the accretion region temperature (derived above) only provides \( E = 4kT = 31 \) eV. A temperature near 20 million kelvin (20 keV) is necessary to begin to excite these Ne inner shell transitions. Thus, if we are to believe the Ne viii spectral features are real, we must invoke an additional heating source in the white dwarf atmosphere at or near the accretion region.

Ramsey et al. (1994) found that essentially all polar spectral energy distributions in the hard and soft (EUV) X-ray region are best fitted by a two-temperature model (an absorbed few 100,000 K blackbody plus a harder thermal bremsstrahlung component). Typical shock temperatures (thermal bremsstrahlung fits) derived for X-ray observations of polars were found to be of order 15–30 keV, quite sufficient to produce Ne vii. Schwpe et al. (2001a) modeled HU Aqr with a bremsstrahlung component having a temperature of 20 keV, consistent with Ramsey et al. and sufficient to produce the neon lines. Thus for HU Aqr, Ne vii absorption features superposed on a blackbody spectrum would be consistent with a two-temperature model for the high-energy emission from the accretion region in a polar. The existence of a harder component is believed to indicate that there is significant external heating of the white dwarf atmosphere by the bremsstrahlung radiation (an irradiated atmosphere) at and near the accretion region.

Polar mass are known to show a “soft X-ray excess” (Ramsay et al. 1994; Warren & Mukai 1996), that is, the ratio \( L_{EUV}/L_{X-ray} \) is greater than the value of 0.55 predicted from theory (King & Watson 1987). Given that we have (nonsimultaneous) EUV and X-ray observations of HU Aqr in both low and high states, let us determine its soft X-ray excess during these times. From our 1998 high accretion state and 1996 low accretion state EUV observations, we find \( L_{EUV}^{high} = 1.16 \times 10^{32} \) ergs s\(^{-1}\) and \( L_{EUV}^{low} = 3.5 \times 10^{31} \) ergs s\(^{-1}\). Using the X-ray flux observed during the similar 1993 high accretion state seen by ROSAT (Schwpe et al. 2001b), we find \( L_{X-ray}^{high} = 2.0 \times 10^{31} \) ergs s\(^{-1}\). Low mass accretion states (such as during 1996–1997) have X-ray fluxes that are about 20 times lower overall than during a high state, thus \( L_{X-ray}^{low} = 1.0 \times 10^{30} \) ergs s\(^{-1}\). Schwpe et al. (2001a) showed that during the accretion region eclipse, HU Aqr was detected with \( L_{X-ray}^{low} = 2.2 \times 10^{29} \) ergs s\(^{-1}\) (\( \sim 0.2 L_{EUV}^{low} \)) apparently due to chromospheric activity on the secondary star. Using these determinations of the high-energy luminosity of HU Aqr, we find \( L_{EUV}/L_{X-ray}^{high} = 5.8 \) and \( L_{EUV}/L_{X-ray}^{low} \geq 35 \).
Both of our luminosity ratios are within the range determined for HU Aqr by Ramsay et al. (1994) of 3.1 (with a range of 1.5–33.4) during an apparent 1992 low mass accretion state \((L_{\text{X-ray}} = 1.9 \times 10^{30} \text{ ergs s}^{-1})\). While it appears that the soft X-ray excess in HU Aqr is greater during low mass accretion states, the range presented by Ramsay et al. is typical of what one finds within the uncertainties of model fitting with the low mass accretion states being of higher uncertainty because of their lower signal. If the deposition of mass blobs below the white dwarf surface is the cause of the soft X-ray excess as currently believed (see King 1995), our results may indicate that accretion by dense mass blobs during times of lower \(M\) occur in a larger proportion compared with accretion of lower density gas.

4.2. Infrared: Light Curves

It is reasonable to assume that the increase in infrared flux from 1996 to 1998 is directly related to the increased mass accretion state in HU Aqr, as evidenced by the much brighter EUV flux. The EUV flux increase is both a result of the thermal increase and the size increase of the accretion region on the surface of the white dwarf (see Table 1). However, where does the excess infrared emission emanate from? The three most likely sources are the thermal emission from the accretion region, cyclotron emission from the accretion region and column, and thermal emission from the accretion stream.

In Figure 7, the secondary-star contribution to the infrared light curves has been subtracted away from the 1998 observations by scaling the ellipsoidal variation model from Ciardi et al. (1998) to the bottom of the stellar eclipse. The ellipsoidal subtracted infrared light curves still show modulations spanning nearly an order of magnitude, of a complex nature, and no longer double humped. Interestingly, the strongest excess infrared emission occurs when the accretion region is self-eclipsed by the white dwarf (region 7, faint phase). This fact alone indicates that not all of the IR emission emanates from the accretion region located on the surface of the white dwarf, but rather a significant fraction must come from elsewhere.

The secondary-star–subtracted \(J\) and \(K\) fluxes (Fig. 7) and the EUV light curve (Fig. 1) are normalized to their maximum value and directly compared in Figure 8. Except for the infrared flux being nonzero during the EUV faint phase (region 7), the light curves are similar in morphology. In region 1 (rise), there is a slight increase of infrared flux matching the EUV rise. The infrared rise is nearly twice as long in duration as the EUV rise, probably a result of the infrared emission emanating from a region more extended than the EUV-emitting region.

The overall decline of the EUV flux across regions 2–4 (the dip phases) is matched in general by the infrared light curves. However, unlike the EUV, the general infrared flux decrease across the dip phases is not a result of the accretion column passing in front of the emission region, but is likely the result of a change in the viewing angle of the beamed cyclotron emission (see Wickramasinghe & Ferrario 2000). Cyclotron emission is at its strongest when viewed at an angle of 90° to the magnetic field lines, which, depending on the exact orientation of the accretion column, corresponds to orbital phases of 0.6–0.7 in HU Aqr. It is only in the stream dip (region 4) and possibly in broad dip 2 (region 3) that there is a corresponding dip in the infrared, and it only appears at \(J\). The less than 1% dip in \(J\) is not as large as the EUV dip, which is total (greater than 4%), but it does imply that the accretion stream is more optically thick at \(J\) than at \(K\).

The IR ingress during stellar eclipse (region 5) is similar in length to the ingress observed in the EUV but occurs slightly earlier in phase (see Schwope et al. 2001b). The infrared egress rises sharply with that of the EUV flux, but the total recovery time is significantly longer than in the EUV. The difference in the infrared egress time is likely a result of viewing geometry and the larger IR-emitting volume. As the secondary approaches inferior conjunction, the accretion column is viewed more and more straight on. This orientation will also provide decreasing infrared cyclotron emission. Therefore, at the beginning of stellar eclipse, the projected area of the accretion column is relatively small and quickly eclipsed. However, as the eclipse ends, the accretion column has rotated more perpendicular to the line of sight, increasing the time required to come fully out of eclipse. As the column rotates to a more perpendicular orientation with the viewing angle, the total IR emission increases as we see during the faint (region 7) phase. This interpretation is slightly complicated by the fact that the level of (beamed) cyclotron emission from the accretion column is also dependent upon the line-of-sight viewing angle.

It would not be surprising if cyclotron emission dominates the infrared emission during the phases when the EUV accretion region is in view. However, can cyclotron
emission contribute significantly during other phases, particularly the EUV faint phase (region 7), or will the infrared emission be dominated by thermal emission from the coupling region and accretion stream? To test these ideas, the $J$ data were resampled at the $K$ data rate. Because the $J$ and $K$ data were obtained in a sequence ($K, J, K, J, \ldots$), for each $K$ point, the two adjacent $J$ points in time were fitted with a low-order spline, and the best-estimate $J$ value was then interpolated for the exact time of each $K$ data point. The intensity ratio of the $J$ flux to the $K$ flux was determined as a function of orbital phase and is shown in Figure 9.

Blackbody radiation, on the Rayleigh-Jeans tail, follows a $\lambda^{-4}$ distribution that corresponds to a $J/K$ flux ratio of $\sim 11$.\(^5\) Cyclotron radiation, however, has a more complicated wavelength dependence. At long wavelengths, the "continuum" consists of optically thick emission that follows a Rayleigh-Jeans wavelength dependence. For magnetic field strengths typical of those in most polars, the optical and infrared spectral regions show the cyclotron continuum to be highly modulated by harmonic structures called cyclotron humps. The spectral dependence of cyclotron emission falls to a much shallower value (near $\lambda^{-1.5}$ to $\lambda^{-2.4}$) within the regions that are modulated by cyclotron humps, with the slope becoming steeper as one moves to earlier harmonics.

Glenn et al. (1994) observed cyclotron harmonics 4, 5, and 6 in the optical spectrum of HU Aqr and fitted them with a 10 keV plasma cyclotron model and a white dwarf magnetic field strength of 36 MG. These results have been confirmed by Schwone et al. (2001b). Thus, the first three cyclotron harmonics in HU Aqr will modulate the continuum in the $J$, $H$, and $K$ bands, as was pointed out by Ciardi et al. (1998). This interpretation is also consistent with model cyclotron spectra for a 10 keV plasma and $B = 35$ MG calculated by Wickramasinghe & Ferrario (2000; see their Fig. 32). Therefore, using a $\lambda^{-2.4}$ dependence for the IR cyclotron spectrum in HU Aqr, we would expect a $J/K$ flux ratio of $\sim 4.3$ if the flux output is dominated by cyclotron emission.

Figure 9 reveals that the flux ratio ($F_{1,2}/F_{2,3}$) is generally flat throughout the orbit of the system, never climbing above $-4.8$ except during the stream dip and fall phases (regions 4 and 6). In the faint phase (region 7), the ratio is almost exactly 4.3, making the EUV faint-phase infrared emission consistent with being essentially pure cyclotron emission. This is somewhat surprising given that the white dwarf has self-eclipsed the accretion region during these phases. However, during this high mass accretion state, the accretion column may extend far enough above the white dwarf surface such that significant cyclotron emission is visible even during the time when the accretion region is self-eclipsed. This is a surprising and unexpected hypothesis.

To see if such a tall accretion column may be possible, we calculate the shock height above the accretion region, that is, the approximate upper limit to where the 10 keV electron plasma would be confined. Using the mass estimate for the white dwarf, 0.6–7 $M_\odot$ (Schwope et al. 2001b), the mass accretion rate during an assumed similar high mass accretion state, $M = 6 \times 10^{-11} M_\odot$ yr$^{-1}$ (Schwope et al. 2001a),
and the expression for the shock height from Frank, King, & Raine (1992, eq. [6.44]), HU Aqr’s shock will extend approximately 0.14R<sub>WD</sub> above the white dwarf surface. Geometric arguments show that if the shock height were at least 0.2R<sub>WD</sub>, it would be visible to an observer even during the EUV faint phase. Schwope et al. (2001b) examine the cyclotron radiation from HU Aqr in detail. They also propose that the cyclotron emission originates from a large height, higher than the soft X-ray emission, but only 0.03R<sub>WD</sub>. Fischer & Beuermann (2001) use one-dimensional hydrodynamic arguments to derive the location from which most of the cyclotron radiation emerges, i.e., the shock height. Applying their formulation to HU Aqr, the height of maximum cyclotron emission is calculated to be near 0.28R<sub>WD</sub>. This value is 2 times that determined from the simple equational form of Frank et al. given above but is similar to the value needed herein to allow cyclotron radiation to be observed at all phases. Thus, given the uncertainties in the values used for these calculations, it seems plausible that significant cyclotron emission is observable throughout the orbit of HU Aqr during high mass accretion states.

The overall increase in the J/K flux ratio from phase 0.7 to phase 1.1 and its peak near phase 1.05 are likely a result of the relative increase of the thermal IR emission from the accretion region during the phases for which the observer has the most direct view. Additionally, during these phases the line of sight is increasingly straight onto the accretion column, which decreases the strength of the (beamed) cyclotron emission. Thus, while the overall IR emission is lower in the phase interval 0.7–1.1 (see Figs. 7 and 8), the relative contribution from thermal IR emission is higher, causing a rise in the J/K flux ratio. However, the ratio never approaches 11, as expected for pure blackbody emission, indicating that cyclotron emission remains dominate throughout the orbit.

5. CONCLUSION

We have presented simultaneous EUV and infrared high mass accretion state observations of the polar HU Aqr. The accretion region on the white dwarf shows an increase in temperature and radius by ~2 times compared with results obtained during a low mass accretion state: the temperature increased from 124,000 to 240,000 K, and the radius from 2.2 × 10<sup>7</sup> to 3.7 × 10<sup>7</sup> cm. A two-temperature model, consisting of a hot thermal bremsstrahlung component and an absorbed blackbody component, seems to fit the EUV observations. The EUV and IR photometric observations are shown to have a correlation with orbital phase, although caused by distinct processes. HU Aqr had mean high-state J and K magnitudes of 14.8 and 14.1, respectively. We have shown that the high mass accretion state, IR light curve, double-humped structure is not due to ellipsoidal variations from the secondary star, but instead is caused by strong geometric modulation of the apparent size of the emitting region. Our results also show that during this high mass accretion state, the IR flux is dominated at all orbital phases by cyclotron emission emerging from high above the white dwarf surface, near 0.2R<sub>WD</sub>.

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REFERENCES

Abbott, M., Boyd, W. T., Jelinsky, P., Christian, C., Miller-Bagwell, A., Lampton, M., Malina, R. F., & Valleraga, J. V. 1996, ApJS, 107, 451
Bowyer, S., & Malina, R. 1991, in Extreme Ultraviolet Astronomy, ed. R. Malina & S. Bowyer (New York: Pergamon), 379
Ciardi, D., Howell, S. B., Hausschildt, P., & Allard, F. 1998, ApJ, 504, 450
Craig, N., et al. 1997, ApJS, 113, 131
Elas, J. H., Froeld, J. A., Matthews, K., & Neugebauer, G. 1982, AJ, 87, 1029 (erratum 87, 1893)
Fischer, A., & Beuermann, K. 2001, A&A, 373, 211
Frank, J., King, A., & Raine, D. 1992, Accretion Power in Astrophysics (Cambridge: Cambridge Univ. Press)
Glenn, J., Howell, S. S., Schmidt, G., Liebert, J., Grauer, A., & Wagner, R. M. 1994, ApJ, 424, 967
Howell, S. B., Ciardi, D., Dhillon, V., & Skidmore, W. 2000, ApJ, 530, 904
Howell, S. B., Geline, D., & Harrison, T. 2001, AJ, 121, 482
Howell, S. B., Mitchell, K. J., & Warnock, A. 1995, AJ, 97, 247
Howell, S. B., Sirk, M., Malina, R. F., Mittaz, J. P. D., & Mason, K. O. 1995, ApJ, 439, 991
Howell, S. B., Sirk, M., Ramsey, G., Cropper, M., Potter, S., & Rosen, S. 1997, ApJ, 485, 333
Hurwitz, M., Sirk, M., Bowyer, S., & Ko, Y. 1997, ApJ, 477, 390
King, A. 1995, in ASP Conf. Ser. 85, Cape Workshop on Magnetic Cataclysmic Variables, ed. D. A. H. Buckley & B. Warner (San Francisco: ASP), 21

King, A., & Watson, M. 1987, MNRAS, 227, 205
Mauche, C. 1999, in ASP Conf. Ser. 157, Annapolis Workshop on Magnetic Cataclysmic Variables, ed. C. Hellier & K. Mukai (San Francisco: ASP), 157
Paerels, F., Heise, J., & van Teeseling, A. 1994, ApJ, 426, 313
Paerels, F., Hur, M., Mauche, C., & Heise, J. 1996, ApJ, 464, 884
Ramsey, G., Mason, K., Cropper, M., Watson, M., & Clayton, K. 1994, MNRAS, 270, 692
Schwope, A., et al. 1998, in ASP Conf. Ser. 137, Wild Stars in the Old West, ed. S. B. Howell, E. Kuulkers, & C. Woodward (San Francisco: ASP), 44
Schwope, A., Schwarz, R., Sirk, M., & Howell, S. B. 2001a, A&A, 375, 419
Schwope, A., Thomas, H.-C., Mantel, K.-H., & Haeftner, R. 2001b, A&A, submitted
Sirk, M., & Howell, S. B. 1998, ApJ, 506, 824
Sirk, M., Valleraga, J. V., Finley, D. S., Jelinsky, P., & Malina, R. F. 1997, ApJS, 110, 347
van Teeseling, A., Heise, J., & Paerels, F. 1994, A&A, 281, 119
Warren, J., & Mukai, K. 1996, in IAU Colloq. 152, Astrophysics in the Extreme Ultraviolet, ed. S. Bowyer & R. Malina (Dordrecht: Kluwer), 325
Warren, J., Sirk, M., & Valleraga, J. 1995, ApJ, 445, 909
Watson, M., King, A., Jones, D., & Moch, T. 1989, MNRAS, 237, 299
Wickramasinghe, D., & Ferrario, L. 2000, PASP, 112, 873