PHASE-RESOLVED HUBBLE SPACE TELESCOPE/STIS SPECTROSCOPY OF THE EXPOSED WHITE DWARF IN THE HIGH-FIELD POLAR AR URSAE MAJORIS

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Received 2000 October 26; accepted 2001 March 7

ABSTRACT

Phase-resolved Hubble Space Telescope (HST)/Space Telescope Imaging Spectrograph (STIS) ultraviolet spectroscopy of the high-field polar AR UMa confirms that the white dwarf photospheric Lyα Zeeman features are formed in a magnetic field of ~200 MG. In addition to the Lyα π and σ+ components, we detect the forbidden hydrogen 1s0 → 2s0 transition, which becomes “enabled” in the presence of both strong magnetic and electric fields. Overall, the combined ultraviolet and optical low-state spectrum is similar to that of the single white dwarf PG 1031+234, in that the optical continuum has a steeper slope than the ultraviolet continuum and that the depth of the Lyα Zeeman lines reaches only 30%–50% of the continuum level. Our attempt in fitting the low-state data with single-temperature magnetic white dwarf models remains rather unsatisfactory, indicating either a shortcoming in the present models or a new physical process acting in AR UMa. As a result, our estimate of the white dwarf temperature remains somewhat uncertain, $T_D = 20,000 \pm 5000$ K. We detect a broad emission bump centered at ~1445 Å and present throughout the entire binary orbit, and a second bump near ~1650 Å, which appears only near the inferior conjunction of the secondary star. These are suggestive of low harmonic cyclotron emission produced by low-level ($M \sim 10^{-13} M_\odot$ yr$^{-1}$) accretion onto both magnetic poles. However, there is no evidence in the power spectrum of light variations for accretion in gas blobs. The derived field strengths are $B \sim 240$ MG and $B \gtrsim 160$ MG for the northern and the southern poles, respectively, broadly consistent with the field derived from the Zeeman lines. The observed Lyα emission line shows a strong phase dependence with maximum flux and redshift near orbital phase $\phi \sim 0.3$, strongly indicating an origin on the trailing hemisphere of the secondary star. An additional Lyα absorption feature with similar phasing as the Lyα emission, but a ~700 km s$^{-1}$ blueshift could tentatively be ascribed to absorption of white dwarf emission in a moderately fast wind. Finally, the high signal-to-noise STIS data provide important information on the intergalactic absorption toward AR UMa. We derive a column density of neutral hydrogen of $N_H = (1.1 \pm 1.0) \times 10^{18}$ cm$^{-2}$, the lowest of any known polar, making AR UMa an excellent candidate for further EUV observations.

Subject headings: line: formation — novae, cataclysmic variables — stars: individual (AR Ursae Majoris) — stars: magnetic fields — white dwarfs

1. INTRODUCTION

AR UMa is a magnetic cataclysmic variable (CV) of the extreme kind. It was discovered as a very luminous soft X-ray source during the Einstein slew survey and optically identified as a nearby ($d = 88$ pc), short-period ($P_{orb} = 1.932$ hr, near the lower edge of the period gap), and possibly magnetic CV by Remillard et al. (1994). An analysis of the Harvard and Sonneberg plate material showed that AR UMa spends most of the time in a state of low accretion activity, $V \sim 16.5$, with sporadic high states reaching up to $V \sim 13.5$ (Remillard et al. 1994; Wenzel 1993). Schmidt et al. (1996) confirmed AR UMa as a strongly magnetic CV (polar) with unprecedented properties: in contrast to all other known polars, AR UMa shows practically no circular polarization during the high accretion state. Moderate circular polarization is, however, observed during the low state, and, if interpreted as dichroism in the photosphere of the white dwarf, indicates a magnetic field $B \gtrsim 200$ MG. Confirmation of an extremely high field ($B \sim 230$ MG) was provided by the detection of the Lyα σ+ Zeeman component in the IUE low-state spectrum of AR UMa (Schmidt et al. 1996). Additional optical (Schmidt et al. 1999) and EUV/X-ray observations (Szkody et al. 1999) constrained the binary parameters and highlighted the central role of the strong magnetic field in the accretion process. Summing up, AR UMa is the first polar that can compete in magnetic field strength with the known single high-field white dwarfs, permitting tests of current theories of magnetically funnelled accretion onto white dwarfs under extreme conditions. Two additional systems were recently identified to bridge the magnetic field strength distribution down to the bulk of the
polars; V884 Her with $B \approx 150$ MG (Schmidt et al. 2001) and RX J1007.5–2016 with $B \approx 90$ MG (Reinsch et al. 1999).

We report in this paper the results of high-quality Hubble Space Telescope (HST)/Space Telescope Imaging Spectrograph (STIS) observations of AR UMa which were aimed at an analysis of the properties of the accreting white dwarf. The new data clearly confirm a field strength of $\sim 200$ MG, though a detailed modeling of the spectra fails for yet unknown reasons. The STIS spectra of AR UMa show some evidence for low-level accretion activity during the low state and such a low interstellar absorption column that the object is an ideal target for future EUV observations.

2. HST/STIS OBSERVATIONS

STIS observations of AR UMa were carried out on 1998 December 9 during five consecutive HST orbits. The optical monitoring of AR UMa reported by Schmidt et al. (1999) shows that the HST data were obtained during a low state ($V \sim 16.5$). The last active phase of AR UMa prior to the HST observations was detected in 1998 October/November at an intermediate magnitude of $V \sim 15.5$. Considering that AR UMa was faint in 1998 June, this active state might have lasted for a maximum of $\sim 5$ months. Unfortunately, during July–September, AR UMa is too close to the Sun, preventing continuous monitoring. The bulk of the STIS data were obtained with the G140L far-ultraviolet (FUV; $1130 - 1710$ Å) grating; only a single short G230L near-ultraviolet (NUV; $1660 - 3150$ Å) exposure was obtained during the last orbit of the visit (Table 1). All data were taken through the $52^\prime \times 0.2^\prime$ slit in order to optimize both throughput and spectral resolution ($R \approx 1000$ and $R \approx 500$ for the G140L and the G230L data, respectively).

2.1. The Average STIS Spectrum

The strongest features detected in the average STIS spectrum of AR UMa (Fig. 1) are the broad absorption troughs of the $\lambda \lambda \pi$ and $\sigma^-$ Zeeman components. This confirms the identification of the absorption line observed at $\sim 1300$ Å in the IUE low-state spectrum as $\lambda \lambda \pi \sigma^-$ split in a field of $\sim 230$ MG (Schmidt et al. 1996). At such field strengths, the $\sigma^-$ component falls shortward of the wavelength range covered by STIS, and the strong decrease in flux observed below 1145 Å is due to the rapid drop of the STIS sensitivity toward shortest wavelengths.

The high-quality STIS data (signal-to-noise ratio $\sim 30$ at 1150 Å $< \lambda < 1450$ Å and $\sim 20$ at 1450 Å $< \lambda < 1750$ Å in the average FUV spectrum) reveals two additional absorption-like structures centered at 1180 and 1415 Å, as well as a number of weak, narrow absorption lines which are most likely of interstellar origin (Fig. 1). Note that the average spectrum contains two narrow $\lambda \lambda \pi$ absorption lines, centered at velocities zero and $\sim -700$ km s$^{-1}$. Finally, the weakness of the detected emission lines, $\lambda \pi \nu 1550$, and $\lambda \nu 22800$, confirms that AR UMa was in a state of very low accretion activity at the time of the HST observations.

2.2. Phase-resolved Ultraviolet Spectroscopy

The G140L data were obtained over 1.7 binary orbits with strong phase overlap between the five exposures. We used the INTTAG and CALSTIS commands of STSDAS to split the G140L data sets (Table 1) into four, five, five, five, and three subexposures, respectively, with individual exposure times ranging from 440 to 592.5 s (corresponding to orbital phase resolutions $\Delta \phi \approx 0.06 - 0.09$). The phases of mid-exposure of the 22 spectra were computed using the ephemeris of Schmidt et al. (1999), where $\phi = 0$ corresponds to the inferior conjunction of the secondary star. Finally, the subexposures were summed up in five phase bins to increase the signal-to-noise ratio (Fig. 2). The spectral fea-

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**Fig. 1.** Right: The average G140L FUV spectrum of AR UMa and the short G230L NUV exposure (see Table 1). The mismatch between the FUV and the NUV spectra is most likely due to the different orbital phase sampling. Left: Blowup of the $\lambda \lambda \pi$ region. Probable interstellar absorption lines are indicated below the spectrum, absorption, and emission features intrinsic to AR UMa are indicated above the spectrum. The shaded region at the bottom gives a measure of the flux error.
and 2.3 m Bok telescope on Kitt Peak. The latter data cover the region 4000–8000 Å at a resolution of ~12 Å, and result from a 300 s exposure (Δφ ~ 0.04) centered at φ = 0.79. The use of these nonsimultaneous data is justified by the fact that the low-state brightness of AR UMa has historically shown very little evidence for change once the system cools from an active phase (Remillard et al. 1994; Schmidt et al. 1996, 1999), and because the continuum (V = 16.9) in the 1998 May data is within 0.1 mag of a V-band measurement obtained 1998 November 14, just 3 weeks prior to the HST observations.

3.1. White Dwarf Temperature

Schmidt et al. (1996) fitted the combined IUE/optical low-state spectrum of AR UMa using a grid of solar abundance nonmagnetic white dwarf model spectra from Hubeny (1988). They found that no satisfying fit can be achieved with a single-temperature model, but that a 15,000 K white dwarf with a 35,000 K spot covering 2% of the white dwarf surface provides a rough match for the data. It is clear that any analysis based on nonmagnetic models is necessarily prone to large uncertainties, as the strong magnetic field has a major impact on the bound-free and bound-bound opacities in the white dwarf atmosphere (e.g., Merani et al. 1995).

Figure 3 illustrates the discrepancy between the observed overall spectrum of AR UMa and nonmagnetic pure hydrogen white dwarf model spectra. The optical spectrum of AR UMa is very blue, almost Rayleigh-Jeans, and can be described well with a 50,000 K nonmagnetic white dwarf model spectrum. In contrast to this, the STIS FUV/NUV spectrum is relatively flat, suggesting T_B ~ 15,000 K. If we assume a distance of 88 pc (Remillard et al. 1994), fitting the flux of the ultraviolet data with the 15,000 K model yields a white dwarf radius of R_{wd} = 10^9 cm, which corresponds to emission from the entire white dwarf. In contrast, the 50,000 K fit to the optical data can only be interpreted as emission from a small spot on the white dwarf. This mismatch of the ultraviolet and the optical continuum is actually the opposite of what is expected from a white dwarf plus hot spot model. In such a configuration, the ultraviolet range is dominated by the hot spot and has a steeper slope than the optical range which reveals the cooler underlying white dwarf (e.g., Gänsicke et al. 2000).

Very similar problems were encountered by Schmidt et al. (1986) when interpreting the ultraviolet and optical spectrum of the single magnetic white dwarf PG 1031 + 234 (B ~ 500 MG). Also in this star, which certainly has no accretion-heated pole cap, the ultraviolet continuum is relatively flat, corresponding to T_{wd} ~ 15,000 K, while the optical continuum is steeper, indicating T_{wd} ~ 25,000 K.

We attempted a better description of the observed ultraviolet plus optical low-state spectrum of AR UMa using the magnetic white dwarf model spectra of Jordan (1992) (see also Putney & Jordan 1995; Burleigh et al. 1999), assuming a magnetic field of B = 200 MG (Schmidt et al. 1996). We computed the spectra for an angle of 20° between the line of sight and the magnetic axis, which corresponds to the closest approach of the magnetic pole to the observer.

2 The extremely steep low-state spectrum of AR UMa was already noted by Remillard et al. (1994), who compared it in their Fig. 1 with the low-state spectrum of AM Her, which has T_{wd} ~ 20,000 K (Heise & Verbunt 1988; Gänsicke et al. 1995).
Fig. 3.—Combined ultraviolet/optical low-state spectrum of AR UMa. The red end of the optical spectrum is dominated by the emission of the M6 secondary star. (a) Illustrative comparison of the AR UMa data to nonmagnetic pure hydrogen white dwarf model spectra with $T_{\text{wd}} = 50,000$ K and $T_{\text{wd}} = 15,000$ K. Both models were normalized to $V = 16.9$, the (assumed) white dwarf magnitude of AR UMa obtained by subtracting an appropriately scaled M6 spectrum from the observed low-state spectrum. (b) Illustrative comparison of the AR UMa data with $T_{\text{wd}} = 25,000, 20,000, 15,000$ K (top to bottom) magnetic white dwarf model spectra ($B = 200$ MG), again normalized to $V = 16.9$. 
(Schmidt et al. 1999). The positions of the Lyα components are well reproduced, confirming the field strength derived by Schmidt et al. (1996). Figure 3 shows the low-state data of AR UMa along with magnetic white dwarf model spectra for $T_{\text{wd}} = 15,000, 20,000,$ and $25,000$ K. The mismatch between the optical and the ultraviolet continuum is somewhat alleviated compared to the fit with nonmagnetic models, but, again, no single-temperature model provides a satisfactory fit to the overall spectrum of AR UMa. The scaling applied to the magnetic model spectra in Figure 3 implies white dwarf radii of $5.1 \times 10^8$ cm and $4.3 \times 10^8$ cm for the 20,000 and the 25,000 K models, respectively, for a distance of 88 pc (Remillard et al. 1994). These values are compatible with the assumption that the low-state spectrum of AR UMa is dominated by emission from the magnetic white dwarf.

We also attempted to model the STIS FUV data alone with our magnetic white dwarf spectra, again with only limited success: Figure 4 shows the best match with $T_{\text{wd}} = 17,000$ K and $R_{\text{wd}} = 8.2 \times 10^8$ cm (for $d = 88$ pc). While the FUV continuum is well described, the model overpredicts the optical flux in the $V$ band by a factor of $\sim 2$. Interestingly, the Zeeman lines of the model spectra are more deeply modulated and have, hence, larger equivalent widths than the observed lines. Again, this is very similar to the observations of PG 1031+234, where the Lyα $\sigma^+$ component is modulated only to $\sim 50\%$ of the continuum flux. Schmidt et al. (1986) argued that the Zeeman transitions can only absorb one of two orthogonal polarization modes of the outgoing flux and, hence, the depth of a saturated line will reach maximally 50\% of the continuum level.

A quantitative prediction of the line depth and strength is complicated, as magneto-optical effects (Faraday rotation and Voigt effect) change the polarization properties of the absorption coefficients throughout the atmosphere. In addition, there is at present no reliable theory for the Stark broadening of the individual Zeeman components in the presence of a strong magnetic field. We carried out two exploratory model atmosphere calculations for $T_{\text{wd}} = 20,000$ K, $B = 200$ MG, once including and once excluding the magneto-optical effects. The strongest transition, the Lyα $\pi$ component, is modulated to $\sim 50\%$ in the spectrum that was computed without magneto-optical effects, just as expected according to Schmidt et al. (1986). However, the $\pi$ component is almost 100\% modulated in the spectrum that was computed including the magneto-optical effects. Similar variations are observed in the $\sigma^+$ and $\sigma^-$ components. We have, thus, to conclude that at present it is not possible to self-consistently model the spectrum of the magnetic white dwarf in AR UMa (or that of PG 1031+234).

Just for completeness, we note that AR UMa as an interacting binary offers two other possibilities to explain the low depth of the Lyα lines: either another component in the binary contributes significantly to the FUV flux, or the white dwarf atmosphere is heated by accretion, resulting in a flatter vertical temperature gradient and weaker absorption lines (as observed, e.g., in AM Her during a high state; Gänscicke et al. 1998). However, neither hypothesis is very appealing, as AR UMa was observed with HST during a state of very low accretion activity.

3.2. The 1180 Å Absorption Line: A Forbidden Lyα 1s₀ → 2s₀ Component in the Atmosphere of the White Dwarf?

In addition to the Lyα $\pi$ and $\sigma^+$ components, a relatively broad (FWHM $\sim 11$ Å) absorption feature centered at

![Fig. 4.—Dashed line: magnetic white dwarf model spectrum with $T_{\text{wd}} = 17,000$ K, $B = 200$ MG and $R_{\text{wd}} = 8.2 \times 10^8$ cm (at $d = 88$ pc). Solid line: STIS FUV data of AR UMa at $\phi = 0.5$ with the 1445 Å cyclotron component (§3.3.3) subtracted. The 1s₀ → 2s₀ transition is discussed in detail in §3.2.](image-url)
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\approx 1180 \, \text{Å} \text{ appears during } \phi = 0.3 - 0.7 \text{ without noticeable variation in wavelength (Fig. 2). Comparison with the phase-resolved HST/GHRS spectra of the single magnetic white dwarf RE J0317−853 suggests that the 1180 Å absorption is due to the normally forbidden dipole transition of hydrogen } 1s_0 \to 2s_0, \text{ which becomes increasingly more probable in the presence of both strong magnetic and electric fields, a situation encountered in the high-density atmospheres of magnetic white dwarfs (Burleigh et al. 1999). In RE J0317−853, the } 1s_0 \to 2s_0 \text{ absorption is attributed to the weaker pole with } B \approx 200 \, \text{MG. In AR UMa, the 1180 Å is strongest at } \phi = 0.3 - 0.5 \text{ when the northern magnetic pole, } B \approx 240 \, \text{MG, is best visible (see §3.3).}
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Both the wavelength and the oscillator strength of the \( 1s_0 \to 2s_0 \) transition in AR UMa depend on the choice of the electric field. The oscillator strength of this "forbidden" feature increases with the electric field at the expense of the normal \( \pi (1s_0 \to 2p_0) \) component. Since we have at present the necessary atomic data only for a limited range of electric field strengths we assumed in our model spectrum calculation (Fig. 4) the same electric field of \( 10^8 \, \text{V m}^{-1} \) as for RE 0317−853 (Burleigh et al. 1999). A detailed modeling of the \( 1s_0 \to 2s_0 \) feature, especially of its phase dependence, will be possible only once the necessary atomic data for a large range of fields are available.

The observed \( 1s_0 \to 2s_0 \) transition in AR UMa is stronger than in the model, in fact of similar strength as the observed \( \pi (1s_0 \to 2p_0) \) component! Therefore, the electric field in the atmosphere of AR UMa should be even higher than that of RE0317−853, which could also explain the slight difference in wavelength between model and observation. Unfortunately, we have no good physical explanation for the origin of such a strong electric field in the atmosphere of AR UMa: The strength of the electric microfield expected from the disturbing particles, ions and electrons, scales with the electron density as \( N_e^{2/3} \), which implies that the electric field increases with the effective temperature because of a higher degree of ionization. From this simple assumption, the electric field strength in AR UMa should be a factor of \( \sim 3 \) lower than in RE 0317−853. A similar conclusion holds for the thermally induced motional Stark effect or the generation of electric fields from a rotating dynamo.

Finally, we add as a cautionary remark that, as the white dwarf in AR UMa is accreting metal-rich material from its secondary, we cannot rule out that heavy elements could contribute to the observed line spectrum. Schmidt et al. (1996) already argued that a number of absorption lines in the optical spectrum could be from elements other than hydrogen. In fact, a broad (FWHM \( \sim 8 \, \text{Å} \) absorption is observed in the STIS spectrum at \( \sim 1335 \, \text{Å} \), as well as a few narrow features that cannot be explained with interstellar absorption (see §4), e.g., \( 1227.7 \) and \( 1325.6 \, \text{Å} \). We note that the \( 1180/1335 \, \text{Å} \) features coincide with \( C \pi \lambda 1176 \) and \( C \pi \lambda 1335 \), which are very strong in the \( \sim 20,000−30,000 \, \text{K} \) metal-rich atmospheres. However, in the absence of theoretical descriptions of metal transitions in strong magnetic fields and as no other typically strong absorption, e.g., near \( Sii \pi \lambda \lambda 1260, 1265 \) or \( Sii \pi \lambda \lambda 1300 \), is observed, we consider the hydrogen \( 1s_0 \to 2s_0 \) transition to be the most likely explanation of the \( 1180 \, \text{Å} \) feature.

3.3. The Broad 1415 Å Absorption

The average spectrum (Fig. 1) contains a strong and broad (\( \sim 70 \, \text{Å} \) absorption-like feature centered at \( \sim 1415 \, \text{Å} \). From Figure 2 it appears that this absorption does not significantly depend on the orbital phase. We envision several possible mechanisms that could be the source of this feature.

3.3.1. Quasi-molecular \( H^+ \) Absorption

In nonmagnetic DA white dwarfs with effective temperatures below \( \sim 20,000 \, \text{K} \), absorption by quasi-molecular hydrogen causes a broad line centered at \( \sim 1400 \, \text{Å} \) (Koester et al. 1985). Schmidt et al. (1996) fitted the combined \( IUE \) optical low-state spectrum of AR UMa with a 15,000 K white dwarf with a small 35,000 K spot (see also the discussion in §3.1). Such a low temperature of the white dwarf makes the \( H^+ \) hypothesis appear viable. However, present theory can not predict the position/shape of the \( H^+ \) absorption in a strong magnetic field. Also on observational grounds, the evidence for \( H^+ \) absorption in magnetic white dwarfs is meager: Gänhsicke et al. (2000) detected \( H^+ \) absorption in only two out of 12 single magnetic white dwarfs that were observed with \( IUE \), and in none of the accreting magnetic white dwarfs in polars observed so far in the ultraviolet.

3.3.2. Zeeman Absorption by Balmer Lines

In extremely strong magnetic fields several transitions of the Balmer line series are shifted by up to thousands of Å into the ultraviolet (e.g., Henry & O’Connell 1985). It may, hence, be also possible that the observed absorption near 1415 Å, the phase-dependent flux variation around 1650 Å, and other structures in the long-wavelength portion of the STIS spectrum, are related to Balmer absorption. Indeed, our model spectra (Fig. 3) qualitatively reproduce the undulations observed in the NUV spectrum of AR UMa, however, they do not contain significant structure in the FUV range (apart from \( Ly\alpha \)).

3.3.3. Cyclotron Emission: Ongoing Accretion

Another possible interpretation arises if the structure near 1415 Å is not due to absorption, but if there is a rather broad emission bump redward of it, peaking at \( \sim 1445 \, \text{Å} \). In the context of accreting magnetic white dwarfs, cyclotron emission is an immediate candidate for the origin of such a broad emission line. As the shape of the feature does not change significantly around the orbit we would have to assume that it originates in a hot accretion plasma near the northern magnetic pole, which remains constantly in view (Schmidt et al. 1999; Szkody et al. 1999). The cyclotron hypothesis finds some support in the fact that an additional bump centered at \( \sim 1650 \, \text{Å} \) appears in the FUV spectrum near \( \phi \approx 0 \). The spectral shape of this bump is most clearly seen in the flux difference (\( \phi = 0.5 \)−\( \phi = 0 \) ) (see Fig. 5b, bottom curve). The appearance of the 1650 Å bump coincides with the phase when the southern accretion region rotates into view (Schmidt et al. 1999; Szkody et al. 1999), and might be related to accretion onto the southern magnetic pole. We recall here that the southern pole is the more active one during the high state.

We model the hypothetical cyclotron features with the emission of an isothermal plasma slab in a strong magnetic field. The intensity spectrum is simply given as \( I_\lambda = B_\lambda (1 - e^{-\tau_\lambda}), \) with \( B_\lambda \) the Planck function and \( \tau_\lambda \) the wavelength-dependent optical depth. We follow the general approach (see, e.g., Wickramasinghe 1988) and express \( \tau_\lambda = \Lambda \phi_\lambda \) with the \( \Lambda \) the dimensionless size parameter and \( \phi_\lambda \) the dimensionless absorption coefficient (computed
Fig. 5 — Cyclotron emission in AR UMa. (a) FUV spectrum for $\phi = 0.5$ (topmost curve) and the cyclotron model derived from the 1445 Å emission bump (bottom curve). The difference of the observed FUV spectrum and the cyclotron model is shifted downward by 0.5 units. The only available NUV spectrum is also shown, but does not match in phase ($\phi = 0.08$). (b) At $\phi \sim 0.0$ the FUV spectrum contains an additional emission bump centered at $\sim 1650$ Å, which we attribute to cyclotron emission from the southern accretion region. Plotted are the observed FUV/NUV spectra centered on/near $\phi = 0.0$ (topmost curves), the cyclotron model for the 1650 Å bump (bottom curve), and the difference of the FUV ($\phi \sim 0.0$) spectrum and both cyclotron models (shifted downward by 0.5 units). Also shown is the FUV flux difference ($\phi = 0.5$) — ($\phi = 0.0$).
according to Channugam & Dulk 1981; Thompson & Cawthorne 1987). Free parameters of this model are the angle δ between the line of sight and the magnetic field line threading the emitting plasma, the magnetic field strength $B$, the plasma temperature $kT$, and the size parameter $\lambda$. The detection of a single cyclotron harmonic does not allow an independent estimate of the magnetic field strength. We computed, therefore, the cyclotron model spectra for a range of field strengths that are compatible with $B \approx 200$ MG, as derived from the Zeeman-split Lyα line (§ 3.1).

In a first step, we modeled the 1445 Å emission bump in the FUV spectrum obtained at $\phi = 0.5$, as it is least contaminated by the emission bump at 1650 Å. We obtain a satisfactory fit for $B = 240$ MG, $kT = 0.45$ keV, $\delta = 35^\circ$, and log ($\lambda$) = 7.0 (Fig. 5a, bottom curve). For these parameters, the 1445 Å bump corresponds to the third harmonic of the cyclotron emission. The model spectrum predicts some emission in the second harmonic at ~2230 Å, and very little flux ($a few 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$) in the fundamental frequency at ~4470 Å. The NUV spectrum shows a small change in slope at ~2100 Å, which might be related to flux from the second harmonic. Subtracting the cyclotron model from the observed FUV spectrum results in an almost smooth continuum (Fig. 5a). The remaining structure is not too surprising, as the accretion region will be characterized by a temperature and density structure which can not fully be described by our simple model.

Subsequently, we modeled the 1650 Å emission bump which appears at $\phi \approx 0.0$ with a second cyclotron spectrum for $B = 160$ MG, $kT = 0.45$ keV, $\delta = 35^\circ$, and log ($\lambda$) = 9.9 (Fig. 5b). This time, the FUV cyclotron bump corresponds to the fourth harmonic. Some emission is predicted in the third ($\sim 2230$ Å) and second ($\sim 3350$ Å) harmonics, and practically no power is expected in the fundamental frequency ($\sim 6700$ Å).

For both emission regions, the derived model parameters imply an emitting area $A_{cyc} \sim 10^{14}$ cm$^2$ and a luminosity $L_{cyc} \sim 10^{30}$ ergs s$^{-1}$. For a canonical white dwarf mass and radius ($0.6 M_\odot$, 8.4 $\times$ 10$^8$ cm), the cyclotron luminosity corresponds to an accretion rate of $\sim 10^{13}$ g s$^{-1}$, or $\sim 1.7 \times 10^{-13} M_\odot$ yr$^{-1}$.

In summary, if the 1445/1650 Å bumps are really due to cyclotron emission, the implication is that a very low inflow of material feeds both the northern and the southern pole during the low state. The low cyclotron flux that both poles emit in the fundamental harmonics is consistent with the nondetection of low-state cyclotron emission (both in polarization and in flux) in the optical range (Schmidt et al. 1996). The derived cyclotron luminosity is somewhat larger than the limit on the low state hard X-ray luminosity obtained from ASCA data (Szkody et al. 1999). The plasma temperature that we derive is extremely low, but compatible with the combination of a low accretion rate and the efficient cyclotron cooling of the postshock flow in a strong field (e.g., Beuermann & Woelk 1996). Fischer & Beuermann (2000) present updated model temperature structures for accretion columns in polars and predict indeed low-temperature ($kT \lesssim 1$ keV) bremsstrahlung from the accretion region for such a combination.

The field strengths derived from the cyclotron emission may be considered an indication that the field geometry is not that of a simple dipole. Such conclusions are not unusual in the studies of single and accreting magnetic white dwarfs (e.g., Wickramasinghe & Martin 1979; Burleigh et al. 1999; Schwoppe et al. 1993). However, the derived 160 MG should be considered as a lower limit on the field strength of the southern pole, as the magnetic south pole remains eclipsed by the white dwarf throughout the entire binary orbit (Schmidt et al. 1999). The detection of cyclotron radiation from the southern accretion region implies that this region is rather extended—which is not too surprising: because of the high magnetic field strength in AR UMa material is already magnetically threaded near the secondary star and may, consequently, be distributed over large areas near the magnetic poles of the white dwarf. The observed weak orbital dependence of the 1445 Å bump requires that the northern cyclotron-emitting region must be located very close ($5^\circ-10^\circ$) to the rotation axis of the white dwarf to minimize the orbital variation of $\delta$. Schmidt et al. (1999) derived from a number of observational constraints a colatitude of the magnetic pole $10^\circ \lesssim \delta B \lesssim 35^\circ$. Keeping in mind that the actual accretion region(s) in polars are usually offset by some degree from the magnetic pole(s), these conclusions are consistent.

4. NARROW ABSORPTION LINES OF LOW-IONIZATION SPECIES: ISM

Besides the broad Lyα Zeeman components, the mean spectrum of AR UMa displays a number of narrow absorption lines of various strengths. An enlargement of the FUV average spectrum (Fig.1) shows that some of the more pronounced narrow absorption features coincide with the strongest interstellar absorption lines that are expected in the spectrum of a nearby galactic ultraviolet bright source (e.g., Gänseicke et al. 1998; Holberg et al. 1999; Mauche et al. 1988). The most convincing detections are Lyα, Si II $\lambda\lambda 1260.4$, and C II $\lambda\lambda 1334.5$ (the latter being embedded in a much broader [FWHM ~ 8 Å] absorption trough that can not be of interstellar origin [see § 3.2]). The interstellar origin of these narrow features is supported by the fact that only the blue component of the Si II $\lambda\lambda 1260.4$, 1264.7 doublet is present in the spectrum of AR UMa. The red component corresponds to a transition from an excited level which is not populated in the interstellar medium. The interstellar lines of Si II $\lambda\lambda 1260.4$ and C II $\lambda\lambda 1334.5$ have equivalent widths of 30–50 mÅ, about half of what is observed in AM Her (Gänseicke et al. 1998). For completeness, we show in Figure 1 the positions of other interstellar transitions of somewhat lower strength than the observed Si II and C II lines, i.e., Si II $\lambda\lambda 1219.70$, 1193.29, N I $\lambda\lambda 1200$, O I $\lambda\lambda 1302.2$, and Si II $\lambda\lambda 1304.4$. We can not claim a significant detection of any of these lines, but we note that all transitions coincide with absorption dips at the noise level.

The observed interstellar Lyα absorption can be used to derive an estimate of the column density of neutral hydrogen along the line of sight to AR UMa. We use for this purpose the FUV spectrum obtained shortly before inferior conjunction of the secondary ($\phi = 0.9$), where the interstellar Lyα profile is least contaminated by the phase-dependent Lyα emission (Fig. 2). We fitted a pure damping profile (Bohlin 1975) folded with a 1.2 Å FWHM Gaussian to the observed Lyα absorption line (Fig. 6, top panel). The resulting column density of neutral hydrogen is $N_H = (1.1 \pm 1.0) \times 10^{18}$ cm$^{-2}$. This value is even lower than that derived by Szkody et al. (1999) from EUVE observations, $N_H = (6-10) \times 10^{18}$ cm$^{-2}$. The higher column density determined from X-ray data indicates the presence of material along the line of sight, presumably within the
binary system, in which hydrogen is ionized to a high degree while the other elements are only partially ionized and still contribute to the soft X-ray absorption. We note in passing that AR UMa is the polar with the lowest column density identified so far. As it is also a very bright EUV source, it is the candidate for future EUV/soft X-ray observations, e.g., searching for spectroscopic evidence of metals in the footpoint of the accretion column.

5. EVIDENCE FOR A WIND IN AR UMa?

The FUV spectrum of AR UMa (Fig. 2) displays phase-dependent Lyα emission, as well as a weak absorption centered at \( \lambda \sim 1213 \) Å (in addition to the interstellar Lyα absorption). Figure 6 (bottom panel), shows the Lyα region of the FUV spectra, corrected for an interstellar absorption of \( N_H \sim 1.1 \times 10^{18} \) cm\(^{-2}\).

We fitted the Lyα emission in all 22 short subexposures \( \phi = 0.5-1.0 \) with Gaussians in order to derive the variation of the flux and the velocity of the line (Fig. 7). The parameters derived for the spectra covering \( \phi = 0.5-1.0 \) are very uncertain, as the Lyα emission almost vanishes during these phases. A sine fit to the emission-line velocities results in a half-amplitude \( K = 367^{+58}_{-58} \) km s\(^{-1}\), a mean velocity \( \gamma = 222^{+43}_{-43} \) km s\(^{-1}\), and maximum redshift occurring at \( \phi = 0.31^{+0.03}_{-0.03} \). These parameters are, apart from the higher \( \gamma \) velocity in the ultraviolet data, very similar to those derived from the radial velocities of Hα and Hβ observed in the low state. Every case of strong Lyα emission occurs with a significant redshift, suggesting that the emitting region is moving away from us at \( \phi \approx 0.3 \). The only component in the binary which is doing this at the given orbital phase is the secondary star (a weak stream would still be expected to show a blueshift or no net velocity near this phase). It seems, therefore, plausible to identify the secondary star as the
The arrival time product of the detectors are photon event tables which list MAMA detectors in the time-tagged mode. The prime data feeding the northern pole could absorb light from the white dwarf around pound. This possibility seems, however, rather unlikely: a alternative origin of the Ly\textsubscript{a} absorption/emission consists of two components, which would also be an explanation for the relatively large width of the Ly\textsubscript{a} emission (see above).

The absorption component at ~1213 Å is also strongest at \( \phi \approx 0.3 \), favoring a common origin of both, the emission and the absorption feature. Identifying the absorption with \( \text{Ly}\text{a} \) yields a velocity of \( \sim -700 \; \text{km s}^{-1} \). The width of the absorption feature is, in contrast to the Ly\textsubscript{a} emission, relatively narrow and indicates a low velocity gradient in the absorbing material. In addition, the wavelength of the absorption component does not vary significantly with the orbital phase. The general shape of the \( \text{Ly}\text{a} \) absorption/emission compound is reminiscent of a P Cygni profile, and, hence, very suggestive of the existence of a moderately fast wind. In a somewhat speculative way, we attribute this \( \text{Ly}\text{a} \) feature to a wind originating from the asymmetrically irradiated secondary star. The narrow, almost stationary absorption corresponds in this case not to the absorption of light from the wind source—the secondary star (as it does not contribute at all to the ultraviolet flux), but could be related to absorption of light from the white dwarf by the intervening wind material.

One may be prone to suggest the accretion stream as an alternative origin of the \( \text{Ly}\text{a} \) absorption/emission compound. This possibility seems, however, rather unlikely: around \( \phi \approx 0.3 \), only the footpoint of the accretion stream feeding the northern pole could absorb light from the white dwarf surface, but has at this point a receding velocity of several 100 km s\(^{-1} \).

6. ULTRAVIOLET LIGHT CURVES

All the STIS data (Table 1) were obtained using the MAMA detectors in the time-tagged mode. The prime data product of the detectors are photon event tables which list the arrival time \( t \) and the detector coordinates \( (x, y) \) for each registered photon. The time resolution of the MAMA’s is 125 \( \mu \text{s} \). This data format permits the extraction of light curves in arbitrary wavelength bands and with any desired time resolution.

6.1. Orbital Flux Modulation

We chose to produce light curves from the G140L observations in the four wavelengths listed in Table 2. The bands were selected to avoid the geocoronal \( \text{Ly}\text{a} \) emission\(^3\) and to provide roughly even sampling over the observed FUV range.

The first step in extracting the light curves is to select appropriate \((x, y)\) regions in the raw two-dimensional detector image which contain the desired wavelength range of the object spectrum, as well as empty background regions above and below the spectrum. We used boxes 35 pixels wide in the cross-dispersion direction to extract the source photons. Care was taken to exclude the area of the detector shadowed by the repeller wire when selecting the background regions. In a second step, two new event tables were created for each wavelength band from all the photon arrival times included in the previously defined source and background \((x, y)\) region(s), respectively. Finally, these two event tables were sampled in equally spaced time bins, i.e., light curves, and the background light curves were subtracted from the source light curves, scaled appropriately for the detector areas used in the extraction process. The light curves were converted from counts s\(^{-1} \) to fluxes by scaling to the average flux in the selected wavelength band. Figure 8 shows the background-subtracted phase-folded light curves in the wavelength bands \( a-d \), sampled in 120 s.

In order to derive amplitudes and phases of the modulations we fitted simple sine functions of the form \( A \sin [(\phi - \phi_0)2\pi] + O \) to the FUV light curves, with \( A \) the half-amplitude of the sine wave, \( \phi_0 \) the phase offset, and \( O \) the mean flux. The best-fit parameters are reported in Table 2.

At first glance, the sinusoidal FUV modulation in AR UMa is reminiscent of the FUV light curves observed in a number of polars during both high and low states and interpreted by rather large “warm” spots near the accretion regions on the white dwarfs (e.g., de Martino et al. 1998; Gänsicke et al. 1998; Stockman et al. 1994). In AR UMa, the phases of maximum flux \( (\phi_{\text{max}} = \phi_0 + 0.25) \) vary between 0.95 and 1.06, which is only slightly later than the phase of maximum EUV flux during the high state. Szkody et al. (1999) convincingly argued that the EUV flux maximum is a result of the appearance of the main accreting (southern) pole during the phase interval \( \sim 0.7-0.1 \).

It seems, hence, very tempting to attribute the observed FUV modulation to a hot spot near the southern accretion region, which is either deeply heated from the previous high state (the cooling timescale of the accretion regions is \( \sim \) months [Schmidt et al. 1996]) or heated by ongoing low-
Fig. 8.—FUV light curves extracted from the time-tagged STIS photon stream in four wavelength bands. From top to bottom: 1146.5–1206.3 Å, 1223.9–1296.9 Å, 1323.2–1520.3 Å, and 1529.1–1717.5 Å. Shown as solid lines are sine fits to the data with the parameters listed in Table 2.

level accretion (§ 3.3.3). However, two points argue against this interpretation:

1. A spot near the southern magnetic pole would be eclipsed by the body of the white dwarf for a large part of the orbital phase, resulting in a flat-bottomed light curve (similar to the EUVE light curve; Szkody et al. 1999), which contrasts with the observed sinusoidal shape of the FUV modulation. To match the observed shape of the FUV light curve, a southern spot would have to be ridiculously large, covering ~70%–90% of the white dwarf, in which case it would be more appropriate to speak of a cold northern polar cap. Thus, if due to a temperature variation over the white dwarf surface, the observed FUV modulation would have to be ascribed to a hot polar cap on the northern pole. But a northern pole cap cannot reproduce the observed modulation, as its aspect changes only little with the orbital phase.

2. The amplitude of the flux modulation is apparently not a simple function of wavelength, but shows a minimum in the 1323.2–1520.3 Å band (Table 2). This is in strong contrast to the FUV modulation observed in other polars, where the amplitude of the FUV modulation has always been found to monotonically increase toward shorter wavelengths. To investigate the wavelength dependence of the FUV modulation in AR UMa, we extracted from the time-tagged photon lists a total of 18 phase-folded light curves each one covering ~30 Å. The signal-to-noise ratio of these light curves is of course lower than that of the four broad-band light curves, and we computed the relative modulation of a given light curve as the ratio of the standard deviation of count rate to the mean count rate in the corresponding wavelength band (Fig. 9).

Fig. 9.—Top: relative modulation of the FUV emission of AR UMa in ~30 Å bands. Bottom: mean FUV spectrum of AR UMa.
As already suggested by the broadband light curves described above, a strong modulation is observed only for $\lambda < 1300$ Å and $\lambda > 1600$ Å. The maximum modulation ($\sim 10\%$) coincides with the $\pi$ component of Ly$\alpha$, the minimum with the “$1415$ Å” absorption feature. Thus, cyclotron emission from the northern pole may dilute the modulation somewhat (§ 3.3.3). However, the cyclotron flux predicted from our model alone is too low to explain the observed decrease of the FUV modulation by a factor $\sim 4$.

Summing up, the interpretation of the FUV modulation observed with STIS cannot follow in a straightforward way the results obtained for other polars. Even though a hot spot may be present in AR UMa, and may contribute to the observed flux modulation, it appears likely that different phenomena cause the observed modulation at the blue and the red ends of the STIS bandpass. At short wavelengths the strong modulation coincides with the Ly$\alpha$ Zeeman absorption structure which sensitively depends on the field dependent photospheric opacities. A slight orbital variation of the projected magnetic field may thus result in a variation of the flux in this band. At long wavelengths, the broad emission bump which appears at $\phi = 0.9$–1.1 and which we interpreted as cyclotron emission best explains the observed flux modulation.

6.2. Probing for Blobby Accretion

In § 3.3.3 we suggested that the bumps observed in the FUV spectrum of AR UMa are due to cyclotron emission, implying that the white dwarf is accreting at a tiny rate even during the low state. We used the STIS time-tagged photon stream to probe for evidence of “blobby accretion,” i.e., for stochastic variability in excess to pure Poisson noise. For this analysis, we extracted a count rate light curve from the STIS photon stream in an analogous fashion as described above, using the entire G140L wavelength range except for a narrow range around the geocoronal Ly$\alpha$ emission. The background-subtracted light curve, sampled in 10 s bins, shows a sinusoidal modulation with an half-amplitude of 3.6%. We computed the discrete power spectrum of this light curve using the MIDAS Time Series Analysis context (Fig. 10). Clearly present is the orbital period plus a number of aliases caused by the uneven sampling of the orbital flux modulation. In order to probe for additional non-Poissonian power, we composed synthetic time-tagged data sets with the same mean count rate and the same coverage as the STIS data. The synthetic count rates were modulated by a sine wave with the parameters derived from the best sine-fit to the STIS count rate light curve. The synthetic data sets were sampled in 10 s bins and, finally, we computed discrete power spectra from the synthetic count rate light curves. The power spectra for the synthetic data sets reproduce very well the power spectrum obtained from the real data, both the various spikes corresponding to aliases of the orbital period and the noise level at high frequencies (Fig. 10). From this comparison, we conclude that the ultraviolet data provide no significant evidence for short-term fluctuations of the count rate due to individual accretion events down to a count rate of $\sim 0.4$ counts s$^{-1}$, corresponding to 0.1% of the mean count rate.

7. SUMMARY

Our analysis of the HST/STIS observations of AR UMa lead to the following results in our understanding of this unique accretion physics and plasma laboratory:

1. We clearly confirm the earlier IUE detection of the photospheric Ly$\alpha$ $\sigma^+$ absorption, and with an implied magnetic field strength of $\sim 200$ MG AR UMa may well be
called “the king of the polars.” Alas, our state-of-the-art magnetic white dwarf model spectra fail to provide a satisfactory description of either the detailed Ly$\alpha$ Zeeman profiles or the ultraviolet/optical spectral energy distribution, resulting in only a rough temperature estimate, $T_{\text{wd}} = 20,000 \pm 5000$ K.

2. The uncooperative (pole-on) viewing geometry prevents a detailed mapping of either the magnetic field topology or a potential temperature variation over the white dwarf surface. Additional information can probably be obtained from the phase dependency of the “forbidden” hydrogen transition. However, detailed modeling must await the necessary atomic data.

3. As a consequence of the high-field strength, the fundamental cyclotron frequency falls in the optical wavelength band. However, there is some evidence in the ultraviolet for low-harmonic cyclotron emission originating from near the magnetic pole and corresponding to a low-state accretion rate of $10^{-13} M_\odot$ yr$^{-1}$. Remnant activity in the system during the low state is also indicated by the presence of Ly$\alpha$ emission. The observed orbital variation of flux and velocity leads us to attribute this emission to the secondary star, possibly to a wind emanating from its trailing hemisphere.

4. The brightness and extremely low interstellar column mark AR UMa as the best polar for future FUV/EUV observations.

Support was provided through NASA grant GO-7397 from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555, by the DLR grants 50 OR 99 036 and DLR 50 OR 96 173, and by the DFG grant KO 738/7-1. We thank A. Fischer for providing us the cyclotron emission model.

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