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ORFEUS-SPAS II OBSERVATIONS OF ALGOL-TYPE INTERACTING BINARIES

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ABSTRACT

The first results from *ORFEUS-SPAS II* observations of five Algol-type binary systems obtained during the shuttle mission STS-80 in 1996 November/December are reported. Single spectra covering 900–1220 Å of AU Mon, Z Vul, U CrB, and TX UMa were acquired with the Berkeley spectrograph. TT Hya was observed at three phases (0.19, 0.63, and 0.95) to study mass flow and to investigate asymmetry in the circumstellar material in the system. O VI was not detected in any of the binaries, which allows us to place an upper limit on $T_{\rm ion}$ in the high-temperature plasma seen in Algol-type binaries. Circumstellar material, presumably associated with the accretion disk, was detected in Fe III (UV1) in AU Mon. We estimate a particle density in the range 10^8–10^9 cm^{-3} for the region of the disk sampled during the observations. Evidence for mass infall was found in the phase 0.95 spectrum of TT Hya. From the *additional* (redshifted) absorption in N II (1085 Å) and N I (1135 Å), we find evidence for superionization in this plasma and estimate a lower limit of $10^{-12}\ M_\odot\ {\rm yr}^{-1}$ for the current infall rate.

Subject headings: accretion, accretion disks — binaries: close — circumstellar matter — ultraviolet: stars

1. INTRODUCTION

During the past two decades, spacecraft observations in the far-UV (FUV) have revealed considerable information about the nature of the circumstellar (CS) material in close binaries of the Algol type (see reviews by Guinan 1990; Plavec 1989). Components of this plasma which have been found from FUV spectra include a region of mass infall toward the primary (the gas stream), an accretion disk, a high-temperature plasma, and domains of mass outflow (usually near phase 0.5). It was the unexpected discovery of prominent absorption and emission lines of N V, C IV, and Si IV in the *IUE* spectra of Algol-type binaries in the early 1980s that revealed the presence of a high-temperature component to the CS material in Algol-type binaries (Peters & Polidan 1984, hereafter PP84; Plavec 1983). From a study of the absorption lines, PP84 concluded that the above ions are formed by resonance scattering in a plasma (termed the high-temperature accretion region [HTAR]) of $T_{\rm ion} \sim 10^5$ K, $N_e \sim 10^9$ cm^{-3}, and carbon depletion that is most prominent on the *trailing* ($0.5 \lesssim \phi_o \lesssim 0.95$) hemisphere of the system.

Using *IUE* data alone, however, only limited information can be extracted on the conditions in the HTAR and cooler CS material, since there are relatively few useful lines longward of Lyα (see PP84). But the spectral region shortward of 1200 Å is rich in resonance lines from abundant ions formed in a wide range of plasma temperatures that span the conditions expected to exist around Algol primaries. For example, if $T_{\rm ion}$ of the HTAR is substantially higher than 10^5 K, one might expect to observe the O VI resonance lines at 1032, 1038 Å between phases 0.50 and 0.95. Resonance lines longward of 1200 Å that are formed in the cooler CS material (e.g., C II, Si II, and Si III) tend to be found in crowded spectral regions and are often significantly blended with photospheric features. Observations of the massive Algol-type binaries HR 2142 and CX Dra with the *Copernicus* satellite in the late 1970s, however, demonstrated the value of the Fe III resonance multiplet (UV1, $\lambda\lambda$1122–1131) for studying the disk and mass flow in interacting binaries (Polidan & Peters 1980), since the CS absorption component of the feature is strong, and except for λ1122 there is no interstellar contribution. To investigate the conditions in the hot and cooler CS plasma using the lines found in the rich spectral region shortward of Lyα, we obtained FUV spectra of five Algol-type binaries with the Berkeley spectrograph on the *Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometers* (*ORFEUS*) telescope during the *ORFEUS*-(*SPAS*) *II* shuttle mission. We report the first results from this project in this Letter.

2. OBSERVATIONS

The FUV spectra were acquired between 1996 November 21 and December 3 with the Berkeley spectrograph during the *ORFEUS-SPAS II* mission on STS-80. The design of the Berkeley spectrograph is discussed in Hurwitz & Bowyer (1986, 1996), and its calibration and performance during the *ORFEUS-SPAS II* mission are described in Hurwitz et al. (1998). The spectra span the region 900–1220 Å and have a resolution (FWHM) of 95 km s^{-1} or ∼0.33 Å.

Information on the program systems is summarized in Table 1 in order of decreasing spectral type of the mass gainer. The binaries range from wide systems in which the gas stream feeds an accretion disk (AU Mon and TT Hya) to close ones in which the gas stream impacts the photosphere of the gainer (Z Vul, U CrB, and TX UMa). The spectra of AU Mon, Z Vul, U CrB, and TX UMa were taken at a single phase; however, three observations of TT Hya (near the two quadratures and just before primary eclipse) allow us to investigate mass flow and asymmetry in the CS material in this binary.

[1] *ORFEUS-SPAS II* Guest Investigator.

TABLE 1
PROGRAM SYSTEMS

System	Spectral Types	Period (days)	Midexposure (1996 Day UT)	Duration (minutes)	Phase
AU Mon	B3 Ve + F8 III	11.11	326 14:13:08	16.9	0.58
Z Vul	B3 V + A2 III	2.46	336 00:30:28	27.5	0.27
U CrB	B6 V + F8 III–IV	3.45	326 16:02:29	24.3	0.62
TX UMa	B8 V + F2 III–IV	3.06	336 01:43:22	25.7	0.46
TT Hya	B9.5 Ve + K0 III–IV	6.95	327 14:41:04	14.6	0.63
			329 18:36:24	7.7	0.95
			338 09:30:37	6.2	0.19

3. INDIVIDUAL RESULTS

The entire *ORFEUS-SPAS II* spectrum of each of the five program systems is displayed in the composite plot in Figure 1. Only one of the TT Hya spectra ($\phi_o = 0.19$) is shown. The most conspicuous features (labeled in Fig. 1) are Lyδ-Lyβ (950–1026 Å), C II λ1037, N II λ1085, the Si III triplet λλ1108–1113, the Si IV/Fe III multiplets between 1120 and 1140 Å, C III λ1176, and the Si II/S III region near 1200 Å.

3.1. *AU Monocerotis*

AU Mon displays permanent double-peaked Hα emission, a prominent HTAR (PP84), and an interesting *periodic* long-term (411 day) variation of 0.3 mag in its optical light (Lorenzi 1985) that appears to be caused by variable mass transfer (Peters 1994). Phases in the long-term cycle, designated by ϕ_L, are reckoned relative to the time of maximum brightness. In this paper, ϕ_o is used for the standard orbital phase. The *ORFEUS* observation, shown in Figure 1, was made at ϕ_o = 0.58 and $\phi_L = 0.77$. *IUE* data reveal that the gas stream, disk, and HTAR lines vary cyclically with ϕ_L, and N V λλ1239, 1243 tends to be strong at the above orbital phase and epoch in its long-term light cycle. Generally speaking, the *ORFEUS* spectrum is that of a typical B3 V star with $v \sin i \sim 120$ km s^{-1}.

To look for the presence of O VI in the HTAR, the star's spectrum was compared with a synthetic one computed using Kurucz's (1993) code SYNTHE. A Kurucz (1994) model atmosphere of $T_{\rm eff} = 17{,}000$ K and $\log g = 4.0$ was adopted for the analysis, since this model fits the FUV continuum observed with *IUE* (at $\phi_L \sim 0.5$) very well (Peters 1994). This analysis did not reveal any evidence for O VI. A similar analysis of the region near 1200 Å did reveal the presence of excess absorption (beyond the photospheric component) due to S III, however, and suggests that N V was probably present during the *ORFEUS* observations (see PP84). Using the ionization calculations of Shull & Van Steenberg (1982) and from the absence of O VI and the likely presence of N V, we conclude that $T_{\rm ion}$ in the HTAR is between 1 and 2 × 10^5 K.

The *ORFEUS* observations show clear evidence of disk absorption in the Fe III (UV1) resonance lines. This is apparent in Figure 2, where the *ORFEUS* spectrum is compared with one computed using SYNTHE and the model atmosphere from above. Both rotational and instrumental broadening were included in the SYNTHE runs. The "shell" components of the

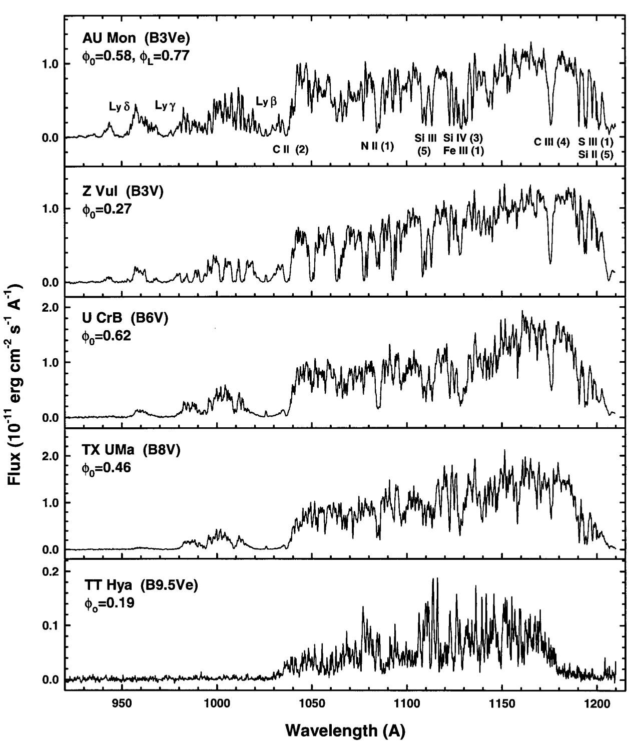

FIG. 1.—Overview of the *ORFEUS-SPAS II* spectra of Algols arranged in order of decreasing spectral type of the mass gainer. The phase of the observation and spectral type of the primary are indicated. Some of the more prominent spectral features are labeled in the top panel. UV multiplet numbers are given in parentheses.

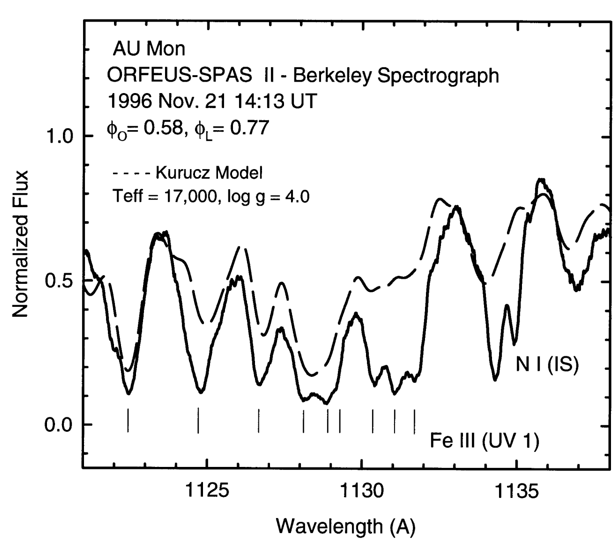

FIG. 2.—Spectrum of AU Mon in the region of Fe III (UV1) compared with a synthetic spectrum computed from a Kurucz model atmosphere that represents the primary. The additional absorption in the Fe III lines is from circumstellar material. Individual components to Fe III are indicated by short vertical lines.

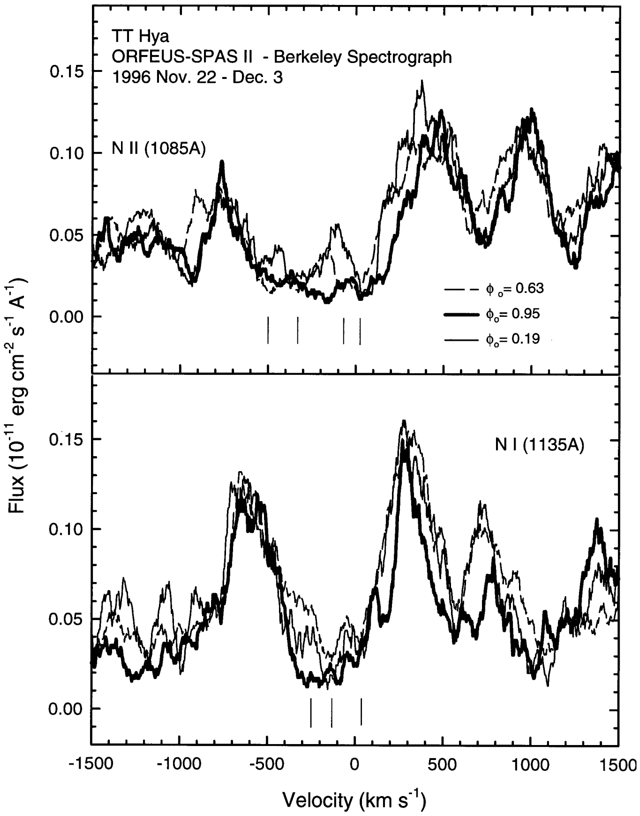

FIG. 3.—Observations of the N II and N I resonance multiplets in TT Hya plotted in velocity space relative to the strongest component at 1085.7 and 1135.0 Å, respectively. Mass infall is evident at phase 0.95 from the additional redward-shifted absorption. Velocities were corrected for spacecraft and binary motion using interstellar lines and the orbital solution of Popper (1989). Short vertical lines show the locations of individual lines in the multiplet.

photospheric features are due to CS material in the disk. After subtracting the synthetic photospheric spectrum, column densities for the nine Fe III features were computed using the linear approximation to the curve of growth:

$$W_\lambda = 8.85 \times 10^{-13} g_i f_{i,k} N_j h \lambda^2/u,$$

where W_λ is the equivalent width of the line in angstroms, g_i is the statistical weight of the lower level, $f_{i,k}$ is the oscillator strength, u is the partition function, $N_j h$ is the column density, h is the path length, and λ is the line's wavelength in microns. The f-values were taken from Kurucz & Bell (1995). The average column density of the nine Fe III lines is 3.5×10^{15} cm^{-2}. If we assume that Fe III is the dominant ionization stage for Fe and a solar abundance (Anders & Grevesse 1989) prevails, we find $N_{\rm tot} h = 1.0 \times 10^{20}$ cm^{-2}. Now the path length, line optical depth, and fractional coverage of the stellar disk are uncertain, but assuming reasonable parameters ($h \sim 1R_*$ or 4 $R_\odot$, unsaturated lines, and 100% coverage of the stellar disk), a total particle density in the range 10^8–10^9 cm^{-3} is implied. It is apparent that AU Mon offers a excellent stellar laboratory for studying processes in accretion disks, but a more detailed analysis of the disk with appropriate treatment of saturated lines, including the velocity field, mass stratification, and likely partial coverage of the stellar disk by the gas, must await observations of higher spectral resolution and higher signal-to-noise ratio (S/N) and full-orbit phase coverage.

3.2. *Z Vulpeculae, U Coronae Borealis, and TX Ursae Majoris*

The *ORFEUS* spectra of these objects were generally consistent with the spectral types of their gainers. Observations of all three systems were obtained at phases during which one would not expect to see lines from highly ionized species (see PP84) or infall from a gas stream. Since these systems are sufficiently close that the gas stream directly impacts the photosphere, a permanent disk cannot form (Peters 1989).

It is interesting to compare AU Mon and Z Vul in Figure 1. One would expect their FUV spectra to be similar, since the optical spectral types of both gainers are the same and the rotational velocity of Z Vul is only slightly smaller than that of AU Mon. The N II λ1085 multiplet, the Si III triplet at 1110 Å, and C III λ1176 have comparable strengths in both stars, but the disk absorption due to Fe III in the 1120–1140 Å region is apparent in AU Mon. In Z Vul, Si IV λλ1122, 1128 dominates in this spectral region. The above is consistent with the expectation that Z Vul, unlike AU Mon, cannot establish a permanent accretion disk. The strong absorption features in Z Vul shortward of 1100 Å are mostly interstellar H_2 lines.

3.3. *TT Hydrae*

TT Hya was one of the first Algol-type binaries noted to display Balmer emission (Wyse 1934). Since then, this system has been studied extensively both in the FUV (Plavec 1988) and in the optical (Etzel 1988; Peters 1989, 1980) regions. Recently, Albright & Richards (1996) mapped the Balmer emitting region using a Doppler tomography code, confirming the presence of an extended accretion disk and probably the presence of the gas stream as well. An illustration showing the Roche geometry and gas stream can be found in that paper (Albright & Richards 1996). The *ORFEUS* observations of TT Hya were obtained at phases 0.19, 0.63, and 0.95, during which our line of sight approximately samples both quadrature orientations and the region of mass infall due to the gas stream.

Comparison of the individual spectra reveals generally more line absorption in the spectrum taken at phase 0.95, but in the relatively unblended regions around the N II λ1085 and N I λ1135 resonance multiplets, it is clear from its redshifted nature that this absorption is due to infalling material (Fig. 3) associated with the gas stream or other flows in the system. Column densities derived from these features were used to find a lower limit to this mass flow. The weak line approximation yields values of 2.6×10^{14} and 1.3×10^{14} cm^{-2}, respectively, for N II and N I. From Shull & Van Steenberg (1982), this implies $T_{\rm ion} \sim 17{,}000$ K, which is much hotter than the gainer's photospheric temperature. Nonradiative processes are apparently producing this superionization. Assuming solar abundances, a total particle density of $\sim 5 \times 10^{18}$ cm^{-2} is implied. The absorbing plasma probably does not cover the star, and the actual features may be saturated. But with these caveats and the assumption that the infall is due to the gas stream, if the width of the stream is $\sim\epsilon$ (the Lubow & Shu 1975 parameter), and the systemic parameters from Etzel (1988), a path length of $\sim 2R_*$, and a flow velocity of 400 km s^{-1} are adopted, we find a mass infall rate of greater than 10^{-12} $M_\odot$ yr^{-1}.

4. SUMMARY

In this Letter, we have presented the first moderate-resolution spectra of classical Algol primaries shortward of 1170 Å. Spectral signatures of an accretion disk and infalling material were seen in AU Mon and TT Hya, respectively. No evidence of O VI was observed in AU Mon ($\phi_o = 0.58$, $\phi_L = 0.77$), even though *IUE* data and additional absorption at S III (UV1) in the *ORFEUS* spectrum indicate that N V should have been present. This suggests that $T_{\rm ion}$ in the HTAR is less than 2×10^5 K.

The Fe III resonance multiplet at 1130 Å (UV1) appears to be a good diagnostic for probing the circumstellar disk. It is a strong multiplet from a relatively abundant ion, and all but one line has a lower level that is sufficiently above the ground state that interstellar lines do not contaminate the data. Disk absorption can easily be seen against the photospheric spectrum. With good phase coverage at 1130 Å and observations of higher resolution and S/N, the physical conditions, asymmetry, and mass flow in the CS material of Algol binaries can be investigated.

The N II and N I resonance multiplets seem useful for determining rates of infall (mass transfer) in Algol systems. If both ions are present (e.g., TT Hya), one can obtain information on $T_{\rm ion}$ in the gas stream. In TT Hya, we found evidence for superionization in the infalling material, as $T_{\rm ion}$ is $\sim 1.5 T_{\rm phot}$. With a fine grid of phase-resolved observations shortward of 1150 Å, one could map out the domain of mass infall in an Algol system and investigate its temperature structure.

A more complete analysis of the *ORFEUS* spectra, including the mass flow in TT Hya, will be presented in a later paper. In particular, we are continuing to study the spectra using the technique of spectrum synthesis to look for abundance anomalies such as carbon depletion or nitrogen enhancement that have been found in the CS and photospheric material of several Algols.

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