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INTERSTELLAR ABSORPTION LINES IN HIGH-RESOLUTION *IUE* SPECTRA OF CATACLYSMIC VARIABLES

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ABSTRACT

High-resolution ultraviolet spectra of five cataclysmic variables obtained with the *International Ultraviolet Explorer* satellite (*IUE*) are used to investigate the character of the interstellar medium in the vicinity of the Sun ($d \lesssim 150$ pc). These spectra reveal narrow absorption features of neutral and singly ionized interstellar species, and, in SS Cyg, narrow velocity-shifted absorption features of C IV, Si IV, and Si III. Using the column densities implied by the absorption features of the neutral and singly ionized species, we obtain values for the depletion of Si, Mg, Mn, and Fe from the gas phase of the interstellar medium in the vicinity of the Sun; the mean neutral hydrogen density; and the column density of neutral hydrogen toward each of our program stars. These hydrogen column densities are of particular importance in constraining the soft X-ray luminosity of cataclysmic variables because of the severe attenuation of the soft X-ray flux of cataclysmic variables by photoelectric absorption in the interstellar medium. In addition, using the column densities implied by the absorption features of C IV, Si IV, and Si III in the spectrum of SS Cyg, we infer the existence of an expanding H II region of interstellar gas photoionized by the EUV and soft X-ray flux of this cataclysmic variable.

Subject headings: interstellar: abundances — nebulae: H II regions — stars: dwarf novae — ultraviolet: spectra

I. INTRODUCTION

By virtue of their strong ultraviolet continua, early-type stars have for over two decades been used as background sources to probe the character of the interstellar medium. In the immediate vicinity of the Sun ($d \lesssim 150$ pc), however, our knowledge of the density and ionization state of the interstellar medium is limited by the small number of nearby early-type stars. Until recently, ultraviolet studies of the local interstellar medium have been limited to solar Lyα and He I λ584 backscattering experiments (e.g., Bertaux 1984, and references therein), Lyα absorption studies toward nearby late-type stars (e.g., McClintock *et al.* 1978, and references therein), Lyα and Mg II absorption studies toward nearby A and late B stars (e.g., Kondo *et al.* 1978), and comprehensive ultraviolet studies of a few lines of sight toward nearby early B and O stars. Because of observational constraints and because of the varying space density of stars, these studies necessarily sample different regions of the local interstellar medium: $d \lesssim 100$ AU for backscattering experiments, $d \lesssim 10$ pc for studies using late-type stars, and $d \gtrsim 20$ pc for studies of the interstellar medium using early-type stars.

With the launch of the *International Ultraviolet Explorer* satellite, it has become possible to add white hot dwarfs to the list of ultraviolet sources which can be used as probes to study the local interstellar medium. To date, high-resolution ultraviolet studies of 10 hot white dwarfs have appeared in the literature (Bruhweiler and Kondo 1981, 1982, 1983; Dupree and Raymond 1982; Sion and Guinan 1983; and Sion, Liebert, and Wesemael 1985). In addition to the standard interstellar absorption features, the ultraviolet spectra of hot white dwarfs often manifest narrow absorption lines of such high-excitation species as C IV, Si IV, Si III, and N V. These lines are invariably (gravitationally) redshifted with respect to the low-excitation interstellar features, although Feige 24 shows an additional absorption component in C IV and Si IV at the velocity of the low-excitation species (Dupree and Raymond 1982) and PG 1034+001 shows an additional absorption component in C IV at the velocity of the low-excitation species (Sion, Liebert, and Wesemael 1985) which are interpreted as arising in a photoionized region in the immediate vicinity of the white dwarf (Dupree and Raymond 1982, 1983).

A class of systems closely related to hot white dwarfs are the cataclysmic variables, which are short-period, semidetached, mass-exchanging binaries containing a white dwarf, a late-type companion, and, typically, an accretion disk. Recent reviews of the properties of cataclysmic variables are supplied by Córdova and Mason (1983) and by Wade and Ward (1985). Because of their high space density, their strong ultraviolet continua, and the expectation that their ultraviolet continua will display no intrinsic narrow absorption features, cataclysmic variables offer a new and unique probe of the interstellar medium in the immediate vicinity of the Sun. We describe herein high-resolution ultraviolet spectra of five cataclysmic

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variables obtained with the *International Ultraviolet Explorer*. As well as showing unprecedented detail in the P Cygni profiles of these systems' C IV, Si IV, and N V resonance lines, these spectra reveal narrow absorption features of neutral and singly ionized interstellar species and, in SS Cyg, velocity-shifted absorption features of C IV, Si IV, and Si III (see Córdova 1986). These spectra are used to investigate the character of the interstellar medium in the vicinity of the Sun, as well as to investigate the origin of the C IV, Si IV, and Si III absorption features in the spectrum of SS Cyg. The outline of this paper is as follows. In § II we present our high-resolution observations. In § III we present an analysis of the narrow absorption features due to (*a*) the neutral and singly ionized (low-excitation) interstellar species, and (*b*) the (high-excitation) species C IV, Si IV, and Si III. In § IV we consider possible interpretations of the origin of the high-excitation absorption features in the spectrum of SS Cyg: an expanding H II region of interstellar gas photoionized by the EUV and soft X-ray flux of this cataclysmic variable, an interstellar bubble blown into the interstellar medium by the wind of SS Cyg, an expanding circumbinary shell, a bow shock formed by the supersonic motion of SS Cyg through the interstellar medium, and a thermal conduction interface between the million degree plasma of the local interstellar medium and the largely neutral gas responsible for the low-excitation absorption features. In § V we briefly consider the implications of our results for the cloud-filling factor of the local interstellar medium. This is followed in § VI by a discussion and summary of our results.

II. OBSERVATIONS

The observations described in this paper were obtained with the *International Ultraviolet Explorer* satellite (*IUE*) through the large aperture at high dispersion with the Short Wavelength Prime (SWP) and the Long Wavelength Redundant (LWR) cameras. The *IUE* satellite and its instruments are described in detail by Boggess *et al.* (1978). The data reduction was performed largely remotely with the data reduction package at the *IUE* Regional Data Analysis Facility at the University of Colorado, although some follow-up analysis on the reduced data was performed with the *IUE* software package at the Center for Astrophysics. Although the U.C. *IUE* RDAF IUESIPS package corrects for temporal and camera head amplifier temperature variations in the location of the spectral format, and routinely reduces the wavelength calibration to a heliocentric scale (e.g., Cassatella, Ponz, and Selvelli 1983; Turnrose and Thompson 1984), the absolute wavelength calibration of these spectra is limited by the accuracy with which the various sources were centered in the large aperture, since a pointing error of one arcsec parallel to the dispersion direction results in a 5 km s^{-1} wavelength shift. Although we quote heliocentric velocities for the interstellar and circumstellar lines in what follows, it must be kept in mind that systematic uncertainties exist as to the absolute wavelength registry of the individual observations.

The data relevant to the *IUE* observations are listed in Table 1. One SWP observation each was obtained of the magnetic variable AM Her and of the nova-like variables RW Sex (BD −7°3007) and V3885 Sgr (CD −42°14462); one SWP and one LWR spectrum was obtained of the nova-like variable IX Vel (CPD −48°1577); and two SWP spectra were obtained of the dwarf nova SS Cyg, one when the system was in outburst, and one when it was in quiescence. (These spectra were obtained by the authors, H. Drechsel, J. Ehnhardt, A. Holm, and K. Mason.) As both AM Her and SS Cyg in quiescence display spectra which are without significant ultraviolet continua, no analysis is possible of the low-excitation interstellar species in these spectra. Both spectra were, however, examined for narrow absorption by C IV, Si IV, and N V superposed on the emission lines of these species. The other spectra reveal strong narrow absorption features of such neutral and singly ionized interstellar species as C II, C II*, N I, Si II, S II, Mg II, Mn II, and Fe II (while absorption by O I λ1302 was obliterated by a reseau).

III. ANALYSIS OF THE NARROW ABSORPTION FEATURES

The narrow absorption features were measured for equivalent width and velocity after smoothing the spectra with a three-pixel running-boxcar filter. Both the placement of the continuum and the determination of the centroid of the individual absorption features was done "by eye." Where it was possible to do so, independent measurements were made of the equivalent widths and velocities of the absorption features which appeared in adjacent spectral orders. The measured values of the equivalent widths for the individual lines in SS Cyg, V3885 Sgr, IX Vel, and RW Sex are listed in Table 2.

TABLE 1

SOURCE INFORMATION

Source	l	b	d[a] (pc)	E_{B-V}[b] (mag)	Sequence Number	Date of Observation	Exposure (minutes)	m_V[c] (mag)
SS Cyg	90°6	+7°1	95	<0.04	SWP 27065[d]	1985 Nov 9	150	9.3
				±0.03	SWP 22263[e]	1984 Feb 14	640	11.9
V3885 Sgr	357°5	−27°8	130	<0.04	SWP 20664	1983 Aug 12	300	10.3
IX Vel	264°9	−7°9	140	<0.04	SWP 18579	1982 Nov 17	180	9.4
					LWR 14656	1982 Nov 17	150	9.4
RW Sex	251°9	+38°7	150	<0.03	SWP 27089	1985 Nov 12	240	10.7
AM Her	77°9	+25°9	75	...	SWP 25330	1985 Feb 27	372	12.9

[a] Distance estimates from Patterson 1984, except for the entry for IX Vel, which is due to us, and is based on the visual magnitude of this object, on an estimate of its inclination and mass accretion rate, and on the visual magnitudes of model accretion disks (Mauche and Raymond 1987).

[b] Reddening values from Verbunt 1987.

[c] Visual magnitude at the time of the observation from the FES counts (Imhoff and Wasatonic 1986) using the $B-V$ values of Bruch 1984.

[d] System in outburst.

[e] System in quiescence.

TABLE 2

MEASURED EQUIVALENT WIDTHS

Ion	λ (Å)	f[b]	Equivalent Width (mÅ)[a]			
			SS Cyg	V3885 Sgr	IX Vel	RW Sex
N I	1199.549	0.133	128^{+14}_{-24}	207^{+12}_{-19}	135^{+5}_{-5}	223^{+16}_{-48}
			...	...	159^{+31}_{-23}	...
	1200.224	0.0885	101^{+12}_{-19}	161^{+23}_{-25}	126^{+15}_{-11}	77^{+59}_{-10}
			...	...	146^{+10}_{-31}	...
	1200.711	0.0442	107^{+13}_{-22}	194^{+19}_{-10}	103^{+8}_{-1}	168^{+14}_{-9}
			...	...	108^{+9}_{-15}	...
S II	1250.586	0.00535	35^{+2}_{-5}	48^{+7}_{-3}	20^{+3}_{-2}	57^{+6}_{-12}
			35^{+6}_{-5}	...	...	...
	1253.812	0.0107	44^{+8}_{-4}	74^{+8}_{-6}	20^{+1}_{-1}	105^{+18}_{-19}
			44^{+6}_{-7}	...	...	...
	1259.520	0.0159	59^{+4}_{-7}	122^{+12}_{-9}	54^{+5}_{-8}	142^{+12}_{-15}
			67^{+1}_{-1}	...	52^{+8}_{-7}	...
C II[c]	1334.532	0.118	~235	~212	~183	~144
C II*	1335.703	0.118	71^{+1}_{-1}	54^{+6}_{-9}	42^{+7}_{-5}	97^{+8}_{-9}
Si II	1190.416	0.251	90^{+21}_{-13}	119^{+34}_{-18}	99^{+9}_{-22}	~77
	1193.289	0.500	96^{+34}_{-25}	200^{+16}_{-13}	108^{+12}_{-16}	~41
	1260.421	0.959	114^{+14}_{-12}	202^{+18}_{-9}	103^{+12}_{-8}	163^{+29}_{-11}
			119^{+17}_{-12}	...	155^{+21}_{-7}	...
	1304.372	0.147	78^{+11}_{-27}	141^{+17}_{-15}	96^{+6}_{-23}	87^{+11}_{-16}
	1526.708	0.23	90^{+7}_{-5}	121^{+10}_{-12}	97^{+30}_{-10}	112^{+7}_{-21}
	1808.012	0.0055	...	...	26^{+5}_{-7}	19^{+10}_{-4}
Fe II	1608.456	0.062	60^{+7}_{-4}	109^{+1}_{-4}	<7	~34
	2343.495	0.108	...	...	152^{+53}_{-1}	...
	2373.733	0.0395	...	...	15^{+3}_{-7}	...
	2382.034	0.328	...	...	128^{+17}_{-10}	...
	2585.876	0.0573	...	...	71^{+9}_{-7}	...
	2599.395	0.203	...	...	174^{+27}_{-50}	...
Mg II	2795.528	0.592	...	...	286^{+9}_{-14}	...
	2802.704	0.295	...	...	256^{+29}_{-12}	...
Mn II	2576.107	0.288	...	...	37^{+2}_{-8}	...
	2593.731	0.223	...	...	~20	...
	2605.697	0.158	...	...	~29	...
V_L[d]	...	...	-14 ± 4	-16 ± 5	$+2 \pm 3$	$+3 \pm 4$
V_C[e]	...	...	−11	−19	+14	+12
C IV	1548.188	0.194	83^{+4}_{-14}	...	...	...
			69^{+25}_{-28}	...	...	...
	1550.762	0.097	50^{+2}_{-2}	...	...	...
			64^{+15}_{-7}	...	...	...
Si IV	1393.755	0.528	43^{+7}_{-12}	...	...	...
	1402.770	0.262	12^{+6}_{-5}	...	...	...
Si III	1206.510	1.66	169^{+9}_{-13}	180^{+20}_{-76}	42^{+5}_{-3}	140^{+40}_{-8}
			...	...	42^{+4}_{-16}	...
V_H[f]	...	...	-34 ± 6	-17 ± 2	-2 ± 2	$+6 \pm 2$

[a] Estimated errors are based only on upper and lower limits to the assumed level of the continuum. Multiple entries for a given line are from independent measurements of the equivalent width in adjacent spectral orders. Multiple entries for the C IV lines of SS Cyg are from the outburst and quiescent spectra.

[b] Oscillator strengths from Morton 1978, except for the values for Si II λ1526, λ1808 and Fe II λ1608, which are from Shull, Snow, and York 1981 and Shull, Van Steenberg, and Seab 1983, respectively.

[c] C II λ1334 equivalent widths are uncertain due to partial contamination by a reseau.

[d] Heliocentric velocity of the low-excitation absorption lines in the SWP camera in units of km s^{-1}.

[e] Heliocentric velocity of the local interstellar medium predicted by Crutcher's 1982 fit to the velocities of the optical interstellar absorption features of stars in the vicinity of the Sun.

[f] Heliocentric velocity of the high-excitation absorption lines in units of km s^{-1}.

The errors on the measured equivalent widths in that table are due only to upper and lower limits to the assumed level of the continuum and do not include any consideration of the noise. Most of the Fe II and all of the Mg II and Mn II equivalent widths are from lines in the long wavelength camera, and so are available only for IX Vel. The average velocities of the low-excitation and high-excitation absorption features in the SWP camera were computed separately, and are included in Table 2. Of the high-excitation species, only Si III appears to have been detected in V3885 Sgr, IX Vel, and (possibly) RW Sex, and in each case this feature shares the velocity of the low-excitation absorption features within the measurement errors (see Fig. 1). In the case of SS Cyg, on the other hand, Si III shares the velocity displacement of -20 ± 7 km s^{-1} of C IV and Si IV with respect to the low-excitation species of this cataclysmic variable (see Fig. 2).

In addition to these measured quantities, we include in Table 2 the value of the velocity of the local interstellar medium for each line of sight based on Crutcher's (1982) fit to the velocity of the optical interstellar absorption features of stars in the vicinity of the Sun ($d \lesssim 100$ pc). The measured velocities differ from Crutcher's values by -3 ± 4, $+3 \pm 5$, -12 ± 3, and -9 ± 4 km s^{-1} for SS Cyg, V3885 Sgr, IX Vel, and RW Sex, respectively. Since the stars in Crutcher's survey show a Gaussian dispersion of approximately 4 km s^{-1} about his fit, only the absorption features of IX Vel can be claimed to be inconsistent with Crutcher's fit to the velocity of the local interstellar medium. Subsequent observations of IX Vel with the Short Wavelength Camera appear to confirm this result: the strongest neutral and singly ionized interstellar absorption features in the short-wavelength spectra SWP 29614–29619 have a mean heliocentric velocity of $\sim +4.5 \pm 2.5$ km s^{-1} compared to Crutcher's value of $+14$ km s^{-1}.[2] However, using higher signal-to-noise ratio spectra and a larger sample of stars, Lallement, Vidal-Madjar, and Ferlet (1986, hereafter LVMF) have shown that the velocity structure of the local interstellar medium ($d \lesssim 100$ pc) is composed of at least four distinct components. While the velocity of the interstellar absorption features in the spectrum of IX Vel differs from Crutcher's velocity by -12 ± 3 km s^{-1}, it differs by -14 ± 3 km s^{-1} from LVMF's "Asterix" velocity component of the local interstellar medium and by only -5 ± 3 km s^{-1} from these author's "Idefix" velocity component, the two strongest components in the Ca II absorption feature of δ Vel, which is $\sim 8°$ away from IX Vel and ~ 120 pc closer to the Sun. The apparent strength of the "Idefix" velocity component relative to the "Asterix" component in the ultraviolet spectrum of IX Vel appears to confirm the tentative conclusion of LVMF that the "Idefix" velocity component of the interstellar medium is more remote from the Sun than the "Asterix" velocity component. Similarly, although the velocity of the interstellar absorption features in the spectrum of RW Sex differs from Crutcher's velocity by -9 ± 4 km s^{-1}, it differs by only -3 ± 4 km s^{-1} from LVMF's "Obelix" velocity component, the strongest component in the Ca II absorption feature of β Crt, which is $\sim 23°$ away from RW Sex; the velocity of the interstellar absorption features in the spectrum of V3885 Sgr differs by only -1 ± 5 km s^{-1} and -3 ± 5 km s^{-1} from LVMF's "Obelix" and "Asterix" velocity components, respectively, the second and third strongest components in α Gru, which is $\sim 26°$ away from V3885 Sgr; and the velocity of the interstellar absorption features in the spectrum of SS Cyg differs by -3 ± 4 km s^{-1} from LVMF's "Asterix" velocity component. Given these results, the velocities of the interstellar absorption features of our sample of cataclysmic variables appear to confirm LVMF's multicomponent model of the velocity structure of the local interstellar medium.

Before curves of growth can be constructed from the equivalent widths in Table 2, a correction must be applied to the equivalent widths of the lines shortward of 1400 Å due to the crowding of the echelle orders at the short-wavelength end of the SWP camera. As Bianchi and Bohlin (1984) have shown, due to the spatial extent of the flux profile of an order perpendicular to the dispersion direction and to the manner in which the background is determined by the IUESIPS software, the

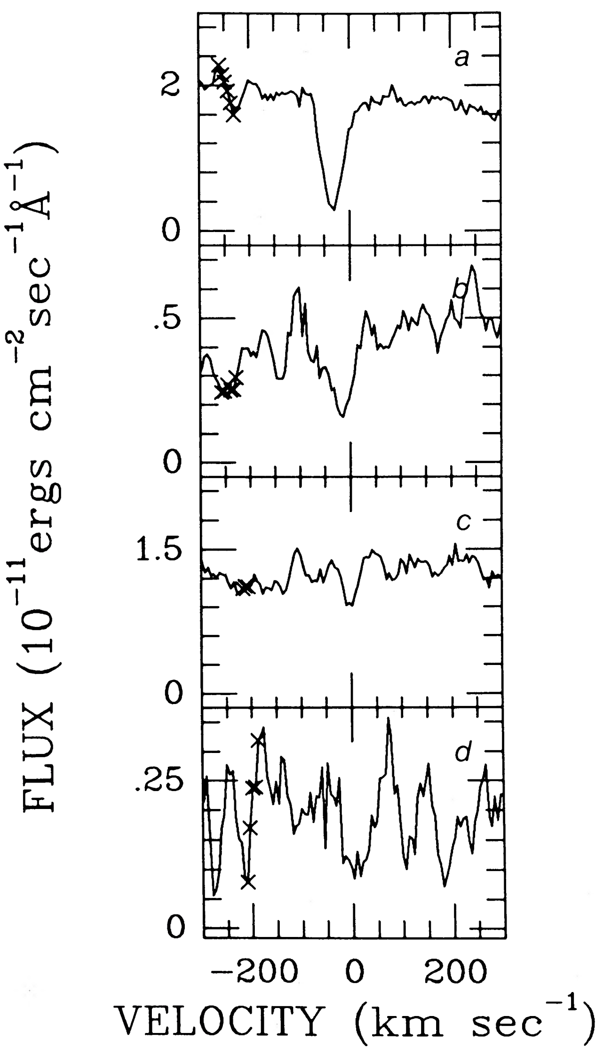

FIG. 1.—Detail of the region of the outburst spectrum of (*a*) SS Cyg, (*b*) V3885 Sgr, (*c*) IX Vel, and (*d*) RW Sex in velocity space for the high-excitation absorption feature Si III. The crosses mark regions of the spectra affected by reseaux.

[2] In contrast, the interstellar absorption features in the long-wavelength spectrum of IX Vel have a mean heliocentric velocity of $+12 \pm 4$ km s^{-1}. However, since the velocities of the interstellar absorption features in the short-wavelength spectra of IX Vel appear to be reproducible, the discrepancy in the velocity between the short- and long-wavelength spectra of IX Vel suggests that the absolute registry of the long-wavelength spectrum of this cataclysmic variable is in error by ~ 10 km s^{-1} due perhaps to a pointing error of $\sim 2''$ parallel to the dispersion direction.

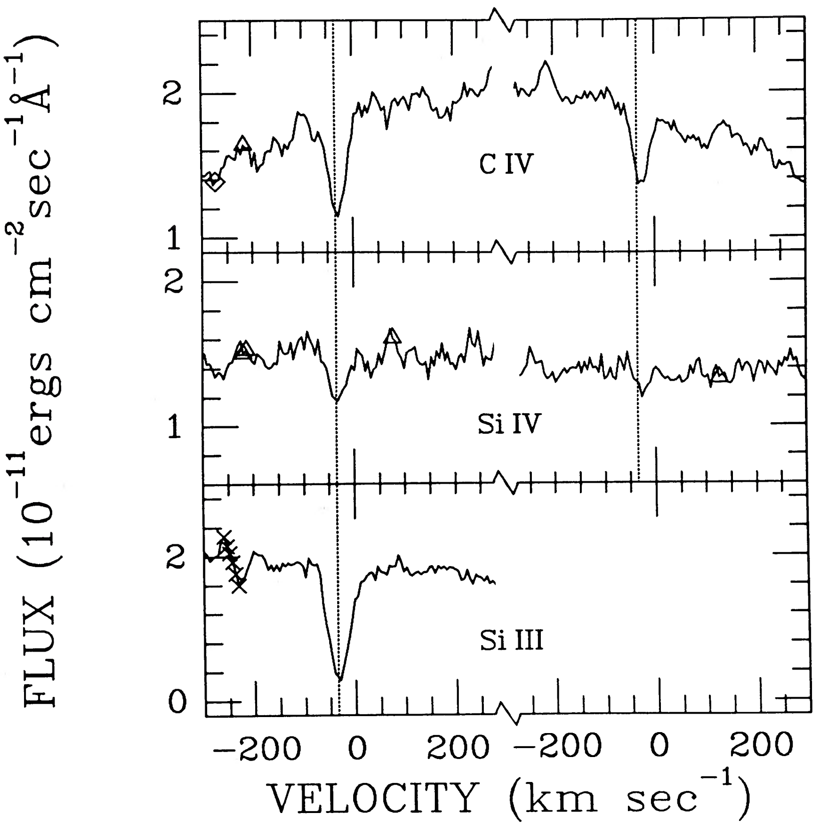

FIG. 2.—Detail of the region of the outburst spectrum of SS Cyg in velocity space for the high-excitation absorption features C IV, Si IV, and Si III. As is indicated by the dotted vertical lines, these features share a heliocentric velocity displacement of ~ -35 km s^{-1}. The various geometric symbols represent various data quality flags: unfiltered bright spots (*diamonds*), extrapolated ITF pixels (*triangles*), and reseaux (*crosses*).

crowding of the echelle orders at the short-wavelength end of the SWP camera results in an overestimate of the background correction to the gross spectral flux shortward of $\sim$1400 Å, a resulting underestimate of the net spectral flux, and a concomitant overestimate of the equivalent widths of the absorption features shortward of $\sim$1400 Å. To account for this effect, Bianchi and Bohlin (1984) give a correction for the net spectral flux extracted by the IUESIPS software. Assuming a flat continuum, this correction results in a fractional change in the net spectral flux F of

$$(F' - F)/\bar{F} \approx 0.984(1 - \lambda/1400) ,$$

(where $\bar{F}$ is the smoothed net spectral flux) which is $\sim$14% at 1200 Å. We applied Bianchi and Bohlin's correction formula to the net spectral flux of SS Cyg at the positions of the N I, C II, C II*, S II, Si II, Si III, and Si IV absorption features shortward of 1400 Å and found that the fractional correction to the net spectral flux between 1200 Å and 1400 Å was described to within 1% by the above approximation formula. Consequently, the correction to the measured equivalent widths EW of the absorption features of SS Cyg shortward of 1400 Å is well fitted by

$$EW' = EW[1 - 0.948(1 - \lambda/1400)] .$$

Since the continuum flux distributions of each of our sources are approximately the same, we applied the above correction to the equivalent widths of each of our sources in Table 2 before a curve-of-growth analysis was attempted of the column densities and depletions implied by the equivalent widths of these lines.

a) *Low-Excitation Interstellar Species*

The column densities of the neutral and singly ionized interstellar species were determined by the curve of growth method (Spitzer 1978) under the simplifying assumption that neither nitrogen nor sulfur are depleted with respect to solar (Allen 1973) abundances in the interstellar medium. Observational support for this assumption is supplied by Ferlet (1981) and Hibbert, Dufton, and Keenan (1985) for nitrogen, and by Gondhalekar (1985*a*) and Harris and Mas Hesse (1986) for sulfur. Given the assumption that these elements are undepleted and that a single broadening parameter describes the curve of growth for all of the neutral and singly ionized species, it is possible to determine the hydrogen column density and broadening parameter for the lines of sight toward each of our program stars, since S II appears to lie on the linear part of the curve of growth, and so determines the hydrogen column density: $N_{\rm H} = N_S/\xi_S$, where ξ_S is the relative solar abundance of sulfur, and $\log N_S = 12.053 + \log (W_\lambda/\lambda) - \log (f\lambda)$ from the relation between $\log (W_\lambda/\lambda)$ and $\log (Nf\lambda)$ on the linear part of the curve of growth. The broadening parameter is determined by the requirement that the curve of growth pass through the data points for the N I lines, which appear in each case to lie on the flat part of the curve of growth. The curves of growth so derived are shown in Figure 3(*a*–*d*). The data points for nitrogen and sulfur appear in these figures as filled squares and circles, respectively; the other symbols represent data for

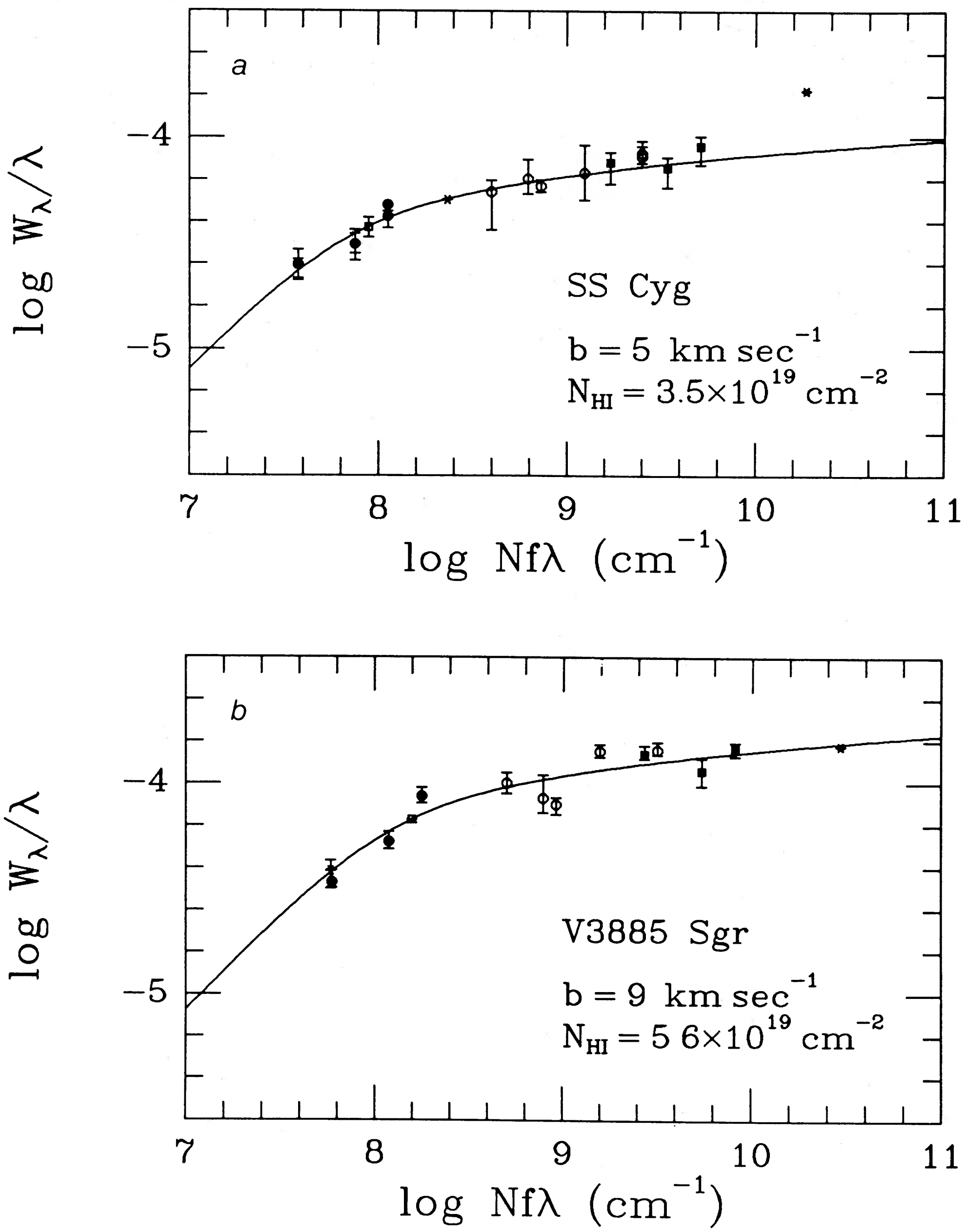

FIG. 3.—Empirical curve of growth for the low-excitation lines in the ultraviolet spectra of (*a*) SS Cyg, (*b*) V3885 Sgr, (*c*) IX Vel, and (*d*) RW Sex. The various symbols represent N I (*filled squares*), S II (*filled circles*), C II (*star*), C II* (*asterisk*), Si II (*open circles*), Fe II (*open squares*), Mg II (*filled triangles*), and Mn II (*open hexagons*). The continuous curve is the theoretical curve of growth for the given value of the broadening parameter *b*. The resulting value of the neutral hydrogen column density is given for each source under the assumption that sulfur is undepleted with respect to solar.

the other ions (C II, C II*, Si II, Mg II, Mn II, and Fe II) whose column densities have been determined by fitting their log (W_λ/λ), log $(f\lambda)$ data points to the various curves of growth. The column densities so derived are listed in Table 3 along with the adopted broadening parameter. Given these column densities, it is a simple matter to determine the depletions of silicon, magnesium, manganese, and iron; these values are listed in Table 4. The paucity of data on magnesium and manganese in Tables 3 and 4 is due to the unfortunate fact that high-resolution long-wavelength ultraviolet spectra exist for only IX Vel.

To see how the depletion values listed in Table 4 compare with the depletions found in the interstellar medium in general, it is instructive to compare our depletion values with the set compiled by Phillips, Gondhalekar, and Pettini (1982) and Van Steenberg and Shull (1988*a*, *b*). Referring to these papers and to Harris, Gry, and Bromage (1984) and Gondhalekar (1985*b*), it is clear that the depletions of silicon, magnesium, manganese, and iron are a relatively strong function of mean hydrogen number density $\langle n_H \rangle = N_H/d$. Given the values of N_H and d from Tables 3 and 1, respectively, the mean hydrogen number densities for our program stars are ~0.12, 0.14, 0.046, and 0.19

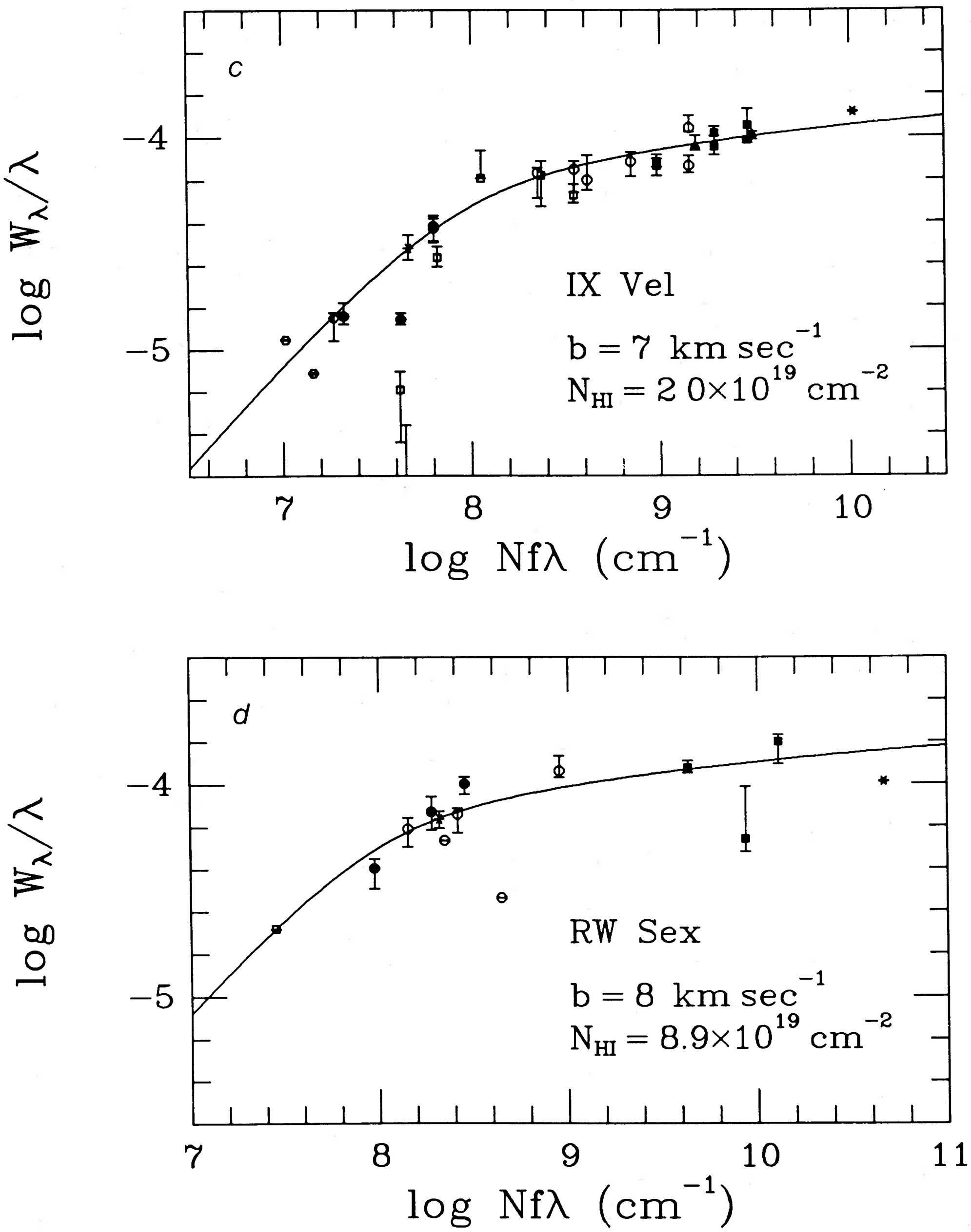

FIG. 3—*Continued*

cm^{-3} for SS Cyg, V3885 Sgr, IX Vel, and RW Sex, respectively. Given these values, our depletion values appear to be consistent with what is observed for other lightly reddened stars, although the depletions of silicon and iron for the line of sight toward RW Sex are larger by a factor of ~ 1.5 compared to the depletions for the lines of sight toward the other three sources. Due to the quality of the data on which this result is based, however, we must appeal for the acquisition of additional high-resolution ultraviolet spectra (in particular LWR spectra) before much can be made of this result.

As indicated above, an accurate measure of the hydrogen column density to each of our program stars can easily be derived under the assumption that sulfur is undepleted from the gas phase of the interstellar medium. One particularly important use of these column densities is that they supply us with a probe of the density of the local interstellar medium on a distance scale ($d \approx 100$–150 pc) which is intermediate between that typical of late-type stars and hot white dwarfs and that typical of early-type stars. Indeed, the hydrogen column densities of our sample of cataclysmic variables probe a region of the interstellar medium currently sampled only poorly by the nearest early-type stars. Like the density of the interstellar medium in the *immediate* vicinity of the Sun (~ 0.1 cm^{-3}), and in contrast to the results for sources within ~ 50 pc, which have column densities less than $\sim 10^{18}$ cm^{-2} and number densities ~ 0.01 cm^{-3} (see, e.g., Bruhweiler 1984, 1987), our sources have column densities greater than $\sim 10^{19}$ cm^{-2} and number densities ~ 0.1 cm^{-3}, consistent with the values typical of other astronomical sources in the distance interval between 50 and 150 pc. These column den-

TABLE 3
TABLE 3

COLUMN DENSITIES

Ion	Log Column Density (cm^{-2}) SS Cyg	V3885 Sgr	IX Vel	RW Sex
H I[a]	19.55	19.75	19.30	19.95
N I	15.51	15.71	15.26	15.91
S II	14.75	14.95	14.50	15.15
C II[b]	16.07	16.27	15.82	16.47
C II*	14.17	13.57	13.47	14.12
Si II	14.32	14.42	14.07	13.87
Fe II	13.95	14.20	13.65	13.45
Mg II	...	...	14.27	...
Mn II	...	...	12.40	...
b_L[a] ($km\ s^{-1}$)	5	9	7	8
C IV	13.45	...	...	...
Si IV	12.60	...	...	...
Si III	$13.19^{+0.55}_{-0.14}$	$13.27^{+0.67}_{-0.16}$	$12.29^{+0.17}_{-0.23}$	$13.02^{+0.32}_{-0.09}$
b_H ($km\ s^{-1}$)	15 ± 5	15 ± 5	$15^{+\infty}_{-10}$	15 ± 5

[a] The values of b_L and $N_{H\,I}$ are derived on the assumption that both nitrogen and sulfur are undepleted with respect to solar. Consequently, $N_X = N_{H\,I}\xi_X$, where ξ_X is the relative solar abundance of both nitrogen and sulfur with respect to hydrogen.

[b] Approximate column densities derived on the assumption that carbon is undepleted with respect to solar.

sities are also consistent with the distributions of hydrogen column density as a function of galactic longitude derived by Frisch and York (1983) and Paresce (1984), particularly the low column density toward IX Vel, which lies in the direction of the "hole" in the interstellar medium in the general direction of Canis Majoris ($l \sim 225°$, $b \sim -15°$). Although the column density to RW Sex is larger than expected from the maps of Frish and York or Paresce for our adopted distance of 150 pc, the distance to this cataclysmic variable may actually be quite a bit larger, as Berriman (1987) has estimated a distance of 400 pc to RW Sex on the basis of the brightness of the red dwarf in this cataclysmic variable.

In addition to this use of the hydrogen column densities in probing the three-dimensional density structure of the local interstellar medium, this parameter is of particular importance in the study of cataclysmic variables. First and foremost, the hydrogen column densities to cataclysmic variables are important because the X-ray spectra of cataclysmic variables in outburst are expected theoretically (see, e.g., Pringle 1977), and indeed are known observationally (e.g., Córdova *et al.* 1980; Córdova *et al.* 1984; van der Woerd, Heise, and Bateson 1986) to be so soft that the flux measured at Earth is drastically reduced by photoelectric absorption in the interstellar medium. In addition to this effect, the energy resolution of proportional counter detectors is so poor at low energies that the parameters characterizing the spectra of cataclysmic variables (typically kT and N_H) are at present only very poorly determined. As a direct result, the soft X-ray luminosities of cataclysmic variables are at present only very poorly determined. By imposing the constraint due to our present observations that the neutral hydrogen column density to this source is $N_{H\,I} \approx 3.5 \times 10^{19}$ cm^{-2}, the wide range of parameters allowed by the X-ray data is greatly reduced. Indeed, if the effective hydrogen column density is set equal to the inferred neutral hydrogen column density $\pm 20\%$, the blackbody temperature is constrained to lie between $kT_{bb} = 35$ eV and 50 eV. If this is the case, the corresponding luminosity of the soft X-ray component of the spectrum of SS Cyg is $L_{sx} \approx 4 \times 10^{32} d_{95}^2$ ergs s^{-1}, where d_{95} is the distance to SS Cyg in units of 95 pc (Patterson 1984; Berriman 1987), whereas the value expected theoretically is approximately 100 times larger: in outburst, $L_{sx} = 0.5 \times G\dot{M}_{accr} M_{wd}/2R_{wd} \approx 4 \times 10^{34}$ ergs s^{-1} for a 1 $M_\odot$ white dwarf accreting at a rate of 10^{-8} $M_\odot$ yr^{-1}, where the factor of 0.5 is included to account for the expectation that roughly half of the luminosity of the boundary layer where the soft X-ray flux is produced will be intercepted by the white dwarf. This discrepancy between theory and observation, if supported by additional observations of additional sources, may prove to have important consequences for our understanding of the soft X-ray luminosity of cataclysmic variables. On the other hand, if photoelectric absorption in a partially ionized wind dominates the absorption of the soft X-ray flux, the effective hydrogen column density will be greater than the hydrogen column density inferred from the low-excitation interstellar absorption features, the thermal bremsstrahlung or blackbody temperatures will be lower, and the soft X-ray luminosities could be more closely in line with theory.

A third importance of the hydrogen column densities of cataclysmic variables is their use in choosing likely candidates for soft X-ray observations. As a confirmative test of this assertion, we note that the two sources for which we have measured the lowest neutral hydrogen column densities, IX Vel and SS Cyg, are also observed to be the strongest soft X-ray sources in our sample. Indeed, from among the nonmagnetic cataclysmic variables listed by van der Woerd (1987) as having *EXOSAT* LE observations (a list which includes V3885 Sgr, IX Vel, RW Sex, and 10 other sources, but which excludes the well-known soft X-ray sources SS Cyg, U Gem, VW Hyi, and OY Car), IX Vel gives the highest counting rate.

Last, by means of the observed relationship between hydrogen column density and reddening, our high-resolution ultraviolet spectral determinations of the hydrogen column densities of cataclysmic variables are capable of supplying us with reddening values for these sources which are independent of any assumption concerning their intrinsic spectral distribution. In addition, they are also capable of supplying us with much smaller reddening values than can typically be obtained by any other method (e.g., by "ironing out" the 2200 Å feature). To illustrate this point, we use Bohlin, Savage, and Drake's (1978) relation between hydrogen column density and reddening for "intercloud" stars, $\langle N_{H\,I}/E_{B-V} \rangle = 5 \times 10^{21}$ cm^{-2} mag^{-1}, and the values of $N_{H\,I}$ listed in Table 3 to obtain E_{B-V}(mag) = 0.007, 0.010, 0.004, and 0.014 for SS Cyg, V3885 Sgr, IX Vel, and RW Sex, respectively. These values are to be compared with Verbunt's (1987) values of E_{B-V} derived from

TABLE 4

ELEMENTAL DEPLETIONS

Element	Elemental Depletion[a] SS Cyg	V3885 Sgr	IX Vel	RW Sex
Si	−0.75	−0.85	−0.75	−1.60
Fe	−1.20	−1.15	−1.25	−2.10
Mg	...	...	−0.45	...
Mn	...	...	−0.30	...

[a] Depletion $\delta_X \equiv \log(N_X/N_H) - \log(N_X/N_H)_\odot = \log[N_X/N_H\,\xi_X]$, where ξ_X is the relative solar abundance of element X with respect to hydrogen, and, strictly, $N_H = N_S/\xi_S$. Both nitrogen and sulfur are assumed to be undepleted with respect to solar.

the strength of the 2200 Å feature: E_{B-V}(mag) = 0.04 ± 0.03, <0.04, <0.04, and <0.03 for SS Cyg, V3885 Sgr, IX Vel, and RW Sex, respectively. Although these values are in rough agreement, we must point out that values of E_{B-V} derived on the basis of the strength of the 2200 Å absorption feature (for example) must be considered more primary than values of E_{B-V} derived on the basis of a *statistical* relationship between E_{B-V} and $N_{\rm H\,I}$ which has not been proved to hold for $N_{\rm H\,I} \lesssim 10^{20}$ cm^{-2}.

b) High-Excitation Species

In exact analogy with the procedure used with the neutral and singly ionized species, the column densities of C IV, Si IV, and Si III were determined from the measurements of the equivalent widths of their absorption lines by the curve-of-growth method. This procedure is simplified greatly for the C IV and Si IV absorption features in the outburst spectrum of SS Cyg since the ratios of the equivalent widths of the resonance doublets of these ions place them on or near the linear part of the curve of growth (see Table 2 and Fig. 4). The same cannot be said of the column densities of the Si III ion, whose equivalent widths in three of our four sources (SS Cyg, V3885 Sgr, and RW Sex) are sufficiently large to place this ion on the flat part of the curve of growth. Consequently, due to the large range of possible broadening parameters, the column densities of Si III in three of our four sources are uncertain by many orders of magnitude. If, however, the broadening parameter is assumed to lie in the range b = 10–20 km s^{-1}, the column densities of Si III are greatly constrained. In the case of SS Cyg, the column density of Si III is constrained to lie in the range log $N_{\rm Si\,III}$(cm^{-2}) = 13.1–13.7. If b = 15 km s^{-1}, the column density of Si III in SS Cyg is only slightly less than the column density C IV: log $N_{\rm C\,IV}$(cm^{-2}) ≈ log $N_{\rm Si\,III}$(cm^{-2}) = 13.2, despite the fact that silicon is less abundant than carbon by an order of magnitude. The ratio of C IV to Si III is even smaller in V3885 Sgr, IX Vel, and RW Sex since C IV (and Si IV) is not observed in these sources. Although the presence of absorption by Si III is uncertain in the case of RW Sex (see Fig. 1), in each of these three sources, the Si III absorption feature appears to share the velocity of the neutral and singly ionized species to within the measurement errors. In SS Cyg, on the other hand, the Si III absorption feature shares the velocity displacement of −20 ± 7 km s^{-1} of the C IV and Si IV absorption features with respect to the absorption features of the neutral and singly ionized species (see Fig. 2). This observation suggests that the absorption features of C IV, Si IV and Si III in the spectrum of SS Cyg are formed in a region distinct from the largely neutral interstellar gas responsible for the absorption features of the neutral and singly ionized species.

As noted previously, SS Cyg was observed with *IUE* at high resolution in outburst and in quiescence. The spectrum obtained when SS Cyg was in quiescence is without a significant ultraviolet continuum and is of sufficiently poor signal-to-noise ratio that an analysis of only the C IV absorption features was possible. The velocities and equivalent widths of these features are listed in Table 2, and are found to be consistent with the values reported by Holm, Ake, and Cassatella (1987).

IV. INTERPRETATION OF THE HIGH-EXCITATION ABSORPTION FEATURES

In the following subsections, we consider five possible interpretations of the origin of the high-excitation absorption features in the ultraviolet spectrum of SS Cyg: (*a*) an expanding H II region of interstellar gas photoionized by the EUV and soft X-ray flux of this cataclysmic variable, (*b*) an interstellar bubble blown into the interstellar medium by the wind of SS Cyg, (*c*) an expanding circumbinary shell, (*d*) a bow shock formed by the supersonic motion of SS Cyg through the interstellar medium, and (*e*) a thermal conduction interface between the million degree plasma of the local interstellar medium and the largely neutral gas responsible for the low-excitation absorption features. Explanations of the high-excitation absorption features involving processes near the binary, e.g., blueshifted narrow absorption components similar to those

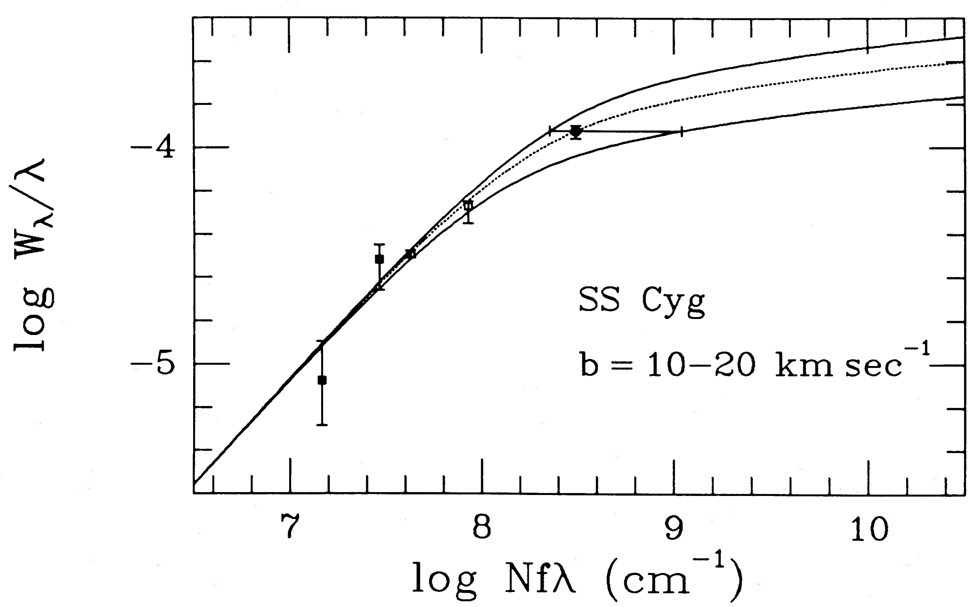

FIG. 4.—Empirical curve of growth for the high-excitation lines in the ultraviolet spectra of SS Cyg. The various symbols represent C IV (*open squares*), Si IV (*filled squares*), and Si III (*filled circle*). The continuous curves are the theoretical curves of growth for b = 10 km s^{-1}, 15 km s^{-1}, and 20 km s^{-1}. The horizontal error bar on the data point for Si III gives the allowed range of column densities for this ion for the given range of broadening parameters.

observed in early-type stars (see, e.g., Cassinelli and Lamars 1987, and references therein) are excluded by the large (~ 90 km s^{-1}) K velocity of the white dwarf in the SS Cyg binary, this system's 396 minute orbital period (Hessman *et al.* 1984), and the 150 minute (SWP 27065) and 640 minute (SWP 22263) integration times necessary to obtain high-resolution ultraviolet spectra of this system in outburst and quiescence, respectively.

a) Photoionized H II *Region*

The narrow absorption features of C IV, Si IV, and Si III in the spectrum of SS Cyg are reminiscent of the absorption features of C IV and Si IV in the ultraviolet spectra of early-type stars. The origin of these features in early-type stars is apparently due to photoionized circumstellar H II regions, although in some cases an additional contribution from more generally distributed interstellar gas appears to be indicated. Black *et al.* (1980) and de Kool and de Jong (1985) have, for instance, concluded that the absorption features of C IV and Si IV in the *IUE* spectra of early-type stars are consistent with an origin in the photoionized H II regions in which these stars are embedded, while Cowie, Taylor, and York (1981) have found that it was necessary to appeal to a truly interstellar contribution (from the hot interstellar gas responsible for the O VI absorption features observed by *Copernicus* [e.g., Jenkins 1978]) to explain the column densities and line profiles for some of their more distant stars. In addition to these studies involving early-type stars, Dupree and Raymond (1983) have shown that hot white dwarfs are capable of producing substantial column densities of C IV and Si IV by photoionization of the interstellar medium. Similar column densities can be expected to be produced by cataclysmic variables as a result of the photoionization of the interstellar medium by the intense EUV and soft X-ray flux produced in their accretion disks and boundary layers.

Although the qualitative aspects of the photoionization of the interstellar medium by cataclysmic variables are similar to early-type stars and hot white dwarfs, the quantitative aspects of the photoionized zone around a star (e.g., a hot white dwarf or cataclysmic variable) which is moving through the interstellar medium differ from those of the photoionized zone around a star (e.g., an early-type star) which is at rest with respect to the interstellar medium. For typical cataclysmic variable velocities and luminosities and typical interstellar densities, the ionized region surrounding a cataclysmic variable is so small that the cataclysmic variable crosses it in about one recombination time. The resulting structure in the interstellar medium is a teardrop-shaped ionization trail (Raymond 1984; Suchkov 1985). Due to the slow recombination of the photoionized interstellar medium, the column densities of highly ionized species in this trail are lowest directly upstream of the ionizing star and highest directly downstream. The column densities toward the ionizing star viewed from any other angle are typically twice the upstream column densities (Raymond 1984).

We have used the time-dependent ionization code described in Raymond (1984) to compute the ionization state of the gas flowing past a cataclysmic variable as it moves through the interstellar medium. The atomic physics package was developed for computing models of astrophysical shock waves (Raymond 1979), and recent improvements to the atomic rates are summarized in Cox and Raymond (1985). For computing the ionization of gas near cataclysmic variables, we held the temperature of the gas constant at 5000 K. The important atomic processes in determining the ionization state of the gas are photoionization by soft X-rays (including the Auger process after *K* shell photoionization); radiative recombination of the helium- and neon-like ions C V, N VI, and Si V; dielectronic recombination of the lithium- and sodium-like ions C IV, N V, and Si IV; and charge transfer. Low-temperature dielectronic recombination was included (Nussbaumer and Storey 1983), and the charge transfer rates are from Butler and Dalgarno (1980).

The luminosity and spectral shape of the ultraviolet and X-ray emission from cataclysmic variables are too poorly known to justify the elaborate calculation necessary to determine the full three-dimensional structure of the ionization trail left behind by a cataclysmic variable as it moves through the interstellar medium. Therefore, we computed the ionization state and column densities of the interstellar gas only along the lines directly upstream and downstream of the cataclysmic variable as a function of the density of the interstellar gas. Models were run assuming that the cataclysmic variable radiates with the spectrum of an optically thick (blackbody) accretion disk (Shakura and Sunyaev 1973) and boundary layer (Patterson and Raymond 1985) accreting at a rate of $10^{-8}\ M_\odot$ yr^{-1}. Since SS Cyg spends $\sim$three-quarters of its time in quiescence and $\sim$one-quarter of its time in outburst, we took the effective luminosity to be $L = \langle L \rangle = \frac{1}{4} G \dot{M}_{\rm accr} M_{\rm wd}/R_{\rm wd} = 4 \times 10^{34}$ ergs s^{-1} appropriate to a 1 $M_\odot$ white dwarf. Such an averaging over outburst and quiescence is allowed, because the ionization and relaxation time of the interstellar medium is much greater than the ~ 50 day recurrence time of SS Cyg in most of the region of interest. In addition to these assumptions, we assumed that the velocity of SS Cyg with respect to the interstellar medium is 30 km s^{-1}. This assumption is justified as follows. The gamma velocity of SS Cyg is measured to be -15 ± 1 km s^{-1} (Hessman *et al.* 1984), while the projected velocity of the interstellar medium in the direction of SS Cyg is measured to be -14 ± 4 km s^{-1} (see Table 1), in agreement with Crutcher's (1982) predicted value of -11 km s^{-1}. Hence, SS Cyg is essentially at rest with respect to the interstellar medium along our line of sight. The (relative) proper motion of SS Cyg, on the other hand, is measured to be 0.1134 ± 0.0033 arcsec year^{-1} (Dahn *et al.* 1982), which corresponds to a tangential space velocity of $\sim 50 d_{95}$ km s^{-1}. Using Crutcher's fit to the velocity of the interstellar medium in the vicinity of the Sun, the corresponding tangential velocity of the interstellar medium in the direction of SS Cyg is ~ 25 km s^{-1} in approximately the same direction as SS Cyg's tangential space velocity. The resulting velocity of SS Cyg with respect to the interstellar medium is therefore ~ 25 km s^{-1}.

The results of our time-dependent calculations of the photionized region around SS Cyg are shown in Figure 5 as a plot of log N_X versus log $n_{\rm ism}$, where N_X is the upstream column density of the X (C IV, Si IV, Si III, and N V) ion and $n_{\rm ism} \approx n_{\rm H}$ is the number density of the interstellar medium. This figure shows that number densities less than 1 cm^{-3} the upstream column densities of C IV, Si IV, Si III, and N V are less than $10^{12.9}$, $10^{12.5}$, $10^{13.2}$, and $10^{11.8}$ cm^{-2}, respectively. Since the column densities of these ions as seen from the side of the teardrop-shaped photoionization zone are typically twice the upstream column densities, the observed column densities of C IV, Si IV, and Si III ($10^{13.5}$, $10^{12.6}$, and $\sim 10^{13.2}$ cm^{-2}, respectively), as well as the lack of a detection of N V, are consistent with the column densities produced by a photoion-

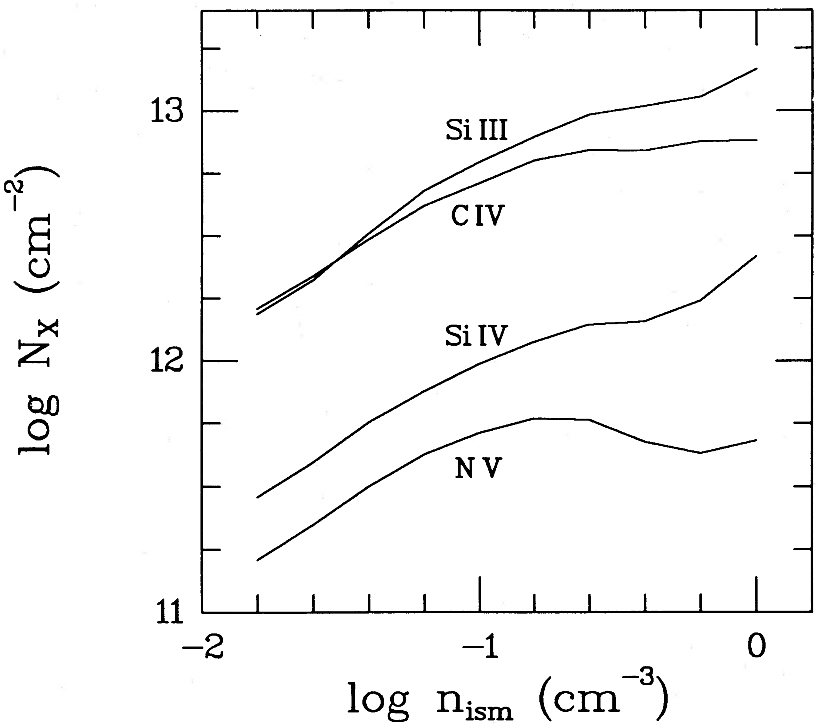

FIG. 5.—Upstream column densities of C IV, Si IV, Si III, and N V as a function of the density of the interstellar medium for a teardrop-shaped photoionized H II region surrounding a cataclysmic variable moving through the interstellar medium with a velocity of 30 km s^{-1}.

ized interstellar H II region having a gas density of (perhaps a few times) 1 cm^{-3}. On the other hand, if the luminosity of the soft X-ray component of the spectrum of SS Cyg is $\sim 1/100$ its theoretical value of $\sim 4 \times 10^{34}$ ergs s^{-1}, as seems to be indicated by observations (see § III*a*), all other things remaining equal, the column density of C IV is reduced by a factor of approximately 2. If this is the case, such an interstellar origin of the C IV, Si IV, and Si III absorption features appears to be excluded.

In addition to the possibility of realizing the required column densities in a photoionized H II region, such an interstellar origin is as well consistent with the widths of the absorption features of C IV λ1548, 1551 and Si III λ1207, which are measured to be 0.18 Å, 0.17 Å, and 0.19 Å (FWHM), respectively (these measured values, and the ones below, include the $\sim$0.1 Å instrumental width of the line). Since the width of the Si II λ1527 absorption feature is measured to be 0.15 Å and the mean width of the N I λ1200 absorption features is 0.16 Å, the widths of the high-excitation absorption features in the outburst spectrum of SS Cyg are broader than the widths of the neutral and singly ionized interstellar absorption features by $\sim$20 km s^{-1}. This additional velocity broadening is sufficiently modest to remove the objection to an interstellar origin for the C IV mooted by Holm, Ake, and Cassatella (1987) based on the apparently large width (0.24 Å) of the C IV absorption features these authors derived from the relatively noisy spectrum of SS Cyg in quiescence. The only potential problem we see in identifying the high-excitation species with a circumstellar H II region is the large ($\sim$20 km s^{-1}) velocity displacement of the high-excitation absorption features with respect to (*a*) the neutral and singly ionized interstellar absorption features and (*b*) the gamma velocity of SS Cyg. If the H II region surrounding SS Cyg is expanding into the interstellar medium, on the other hand, the blueshift of the high-excitation absorption features is to be expected, since the sound speed of the ionized gas, and consequently the expansion velocity of the H II region, is $C = 12T_4^{1/2}$ km s^{-1}, where T_4 is the temperature of the H II region in units of 10^4 K.

b) *Interstellar Bubble*

Since nova-like variables and dwarf novae in outburst lose mass to the interstellar medium in the form of a high-velocity wind, it is possible that the high-excitation absorption features observed in the ultraviolet spectrum of SS Cyg are formed at the surface of the cavity blown into the interstellar medium by the wind of this cataclysmic variable. In addition to being analogous to similar structures produced by early-type stars, this possibility for the origin of the high-excitation absorption features in SS Cyg is suggested by the bow-shock–like emission nebula surrounding the cataclysmic variable 0623+71, a nebula which has every appearance (see, e.g., Krautter, Klass, and Radons 1987) of being an interstellar wind-blown cavity deformed by the motion of this cataclysmic variable through the interstellar medium.

i) *Conduction Front*

As shown by Castor, McCray, and Weaver (1975) and Weaver *et al.* (1977), the interaction of the stellar wind of an early-type star with the interstellar medium leads to the formation of an "interstellar bubble" in the interstellar medium consisting of a central low-density $\sim 10^6$ K shock-heated stellar wind and a shell of relatively cool swept-up interstellar gas separated by a thermal conduction interface, a structure these authors argue is responsible for the O VI column densities observed by *Copernicus*. For the parameters appropriate to an early-type star, Weaver *et al.* found that the column density of

O VI in such a conduction front is $N_{\rm O\,VI} \approx 2 \times 10^{13} L_{36}^{1/35} n_{\rm ism}^{9/35} t_6^{8/35}$ cm^{-2}, where $L_{36} = L_{\rm wind}/10^{36} = \frac{1}{2}\dot{M}_{\rm wind} V_{\rm wind}^2/10^{36}$ is the mechanical luminosity of the wind in units of 10^{36} ergs s^{-1} and t_6 is the age of the system in units of 10^6 years, although Weaver (1977) found that, below $L_{\rm wind} \sim 4 \times 10^{34}$ ergs s^{-1}, $N_{\rm O\,VI} \propto L_{\rm wind}^{0.19}$. The column densities of C IV and Si IV were found to be $N_{\rm C\,IV} = 0.16 N_{\rm O\,VI} \sim 10^{12.5}$ cm^{-2} and $N_{\rm Si\,IV} = 0.01 N_{\rm O\,VI} \sim 10^{11.3}$ cm^{-2}, almost independent of the parameters of the system. Since this conduction front is expanding into the interstellar medium, the absorption features produced by the high-excitation species in this structure will be blueshifted (by $\sim 16 L_{36}^{1/5} n_{\rm ism}^{-1/5} t_6^{-2/5}$ km s^{-1}) with respect to the neutral and singly ionized interstellar absorption features, just as is observed in the ultraviolet spectrum of SS Cyg. Given these results, it is tempting to scale the above expressions for the column densities and expansion velocities found to hold for the parameters appropriate to early-type stars to those of cataclysmic variables, although such a scaling may not be appropriate because of the much smaller size of the interstellar bubble of a cataclysmic variable. If we proceed nonetheless, and assume that the terminal velocity of the wind of a cataclysmic variable is $V_{\rm wind} = 5000$ km s^{-1}, that during outburst the mass-loss rate in the wind is equal to one-tenth the mass accretion rate, $\dot{M}_{\rm wind,o} = 1/10 \dot{M}_{\rm accr,0} \approx 10^{-9}\ M_\odot$ yr^{-1}, and that the cataclysmic variable spends approximately one-quarter of its time in outburst, the time-averaged mass-loss rate is $\langle \dot{M}_{\rm wind} \rangle \approx \frac{1}{4}\dot{M}_{\rm wind,o} \approx 2.5 \times 10^{-10}\ M_\odot$ yr^{-1}, and the resulting mechanical luminosity of the wind is $L_{\rm wind} = \frac{1}{2}\langle \dot{M}_{\rm wind} \rangle V_{\rm wind}^2 \approx 2 \times 10^{33}$ ergs s^{-1}. Although this value is much smaller than the value of the mechanical luminosity of the wind of an early-type star, the dependence of the column densities on $L_{\rm wind}$ is sufficiently weak that the column densities of the high-excitation absorption features in a cataclysmic variable do not differ significantly from those of an early-type star: $N_{\rm C\,IV} \sim 10^{12.2}$ cm^{-2} and $N_{\rm Si\,IV} \sim 10^{11.0}$ cm^{-2}. Unfortunately, these column densities are too small by factors of 20 and 40, respectively, compared to the column densities measured in SS Cyg. Furthermore, the expansion velocity of the interstellar bubble of a cataclysmic variable, and consequently the blueshift of the high-excitation absorption features, is reduced by a factor of approximately 3.5 at a given age relative to the expansion velocity of the interstellar bubble of an early-type star. Given the necessities of higher column densities and expansion velocities than appear capable of being produced in the conduction front of an interstellar bubble of a cataclysmic variable, this explanation for the origin of the high-excitation absorption features in the ultraviolet spectrum of SS Cyg appears to be excluded.

ii) *Photoionized Shell*

If the high-excitation absorption features cannot be formed in the conduction front of SS Cyg's wind-blown interstellar bubble, perhaps they can be formed in the surrounding photoionized shell of swept-up interstellar gas. According to Weaver *et al.* the column density through such a shell is $N = 2.8 \times 10^{19} L_{36}^{1/5} n_{\rm ism}^{4/5} t_6^{3/5}$ cm^{-2}. To realize an expansion velocity of ~ 20 km s^{-1}, the effective age of bubble must be $\sim 2.5 \times 10^4$ yr if the wind luminosity is 2×10^{33} ergs s^{-1}, at which time the radius of the shell is $R_{\rm shell} = 2.6 \times 10^{18}$ cm. Assuming this age, the column density through the shell is $N = 8.8 \times 10^{17} n_{\rm ism}^{4/5}$ cm^{-2}. Consequently, the column density of the X (C IV, Si IV, or Si III) ion is $N_X = 8.8 \times 10^{17} A_X \xi_X n_{\rm ism}^{4/5}$ cm^{-2}, where A_X is the abundance of the element of interest and ξ_X is the ionization fraction of the X ion; the column density of C IV is thus $N_{\rm C\,IV} = 2.9 \times 10^{14} \xi_{\rm C\,IV} n_{\rm ism}^{4/5}$ cm^{-2}, and the column densities of Si IV and Si III are smaller by factors of $10\xi_{\rm C\,IV}/\xi_{\rm Si\,IV}$ and $10\xi_{\rm C\,IV}/\xi_{\rm Si\,III}$, respectively. Referring to Table 3, the requisite column densities of the high-excitation species can thus be produced in the shell if the ionization fractions of C IV, Si IV, and Si III are 0.10, 0.14, and 0.39–1.0, respectively, times $n_{\rm ism}^{-4/5}$. Assuming as before that SS Cyg radiates with the spectrum of an optically thick accretion disk and boundary layer accreting at an effective rate of $2.5 \times 10^{-9}\ M_\odot$ yr^{-1}, we find that the ionization fractions of C IV, Si IV, and Si III at a distance $R_{\rm shell}$ away from the cataclysmic variable are 2×10^{-5}, 9×10^{-3}, and 0.5, respectively, if the density of the material in the shell is $4n_{\rm ism}$ and $n_{\rm ism} = 1$ cm^{-3}. Since these values for the ionization fractions of C IV and Si IV are so much smaller than the values required to explain the observed column densities of these ions, we conclude that the requisite column densities of the high-excitation species cannot be formed in the photoionized shell of swept-up interstellar gas surrounding the interstellar bubble of SS Cyg.

c) Expanding Circumbinary Shell

Alternately, it is possible that the high-excitation absorption features in the spectrum of SS Cyg are formed in an expanding circumbinary shell resulting from a classical nova outburst or as a result of the common-envelope evolution of the binary from which SS Cyg originated. In the former case, assuming an initial ejected envelope mass of $10^{-4.5}\ M_\odot$, an initial ejection velocity of 100 km s^{-1}, and complete sweeping of the interstellar gas, conservation of momentum brings the velocity of the resulting ejected and swept-up shell down to a velocity of 20 km s^{-1} at a radius of $\sim 7 \times 10^{18} n_{\rm ism}^{-1/3}$ cm in $\sim 3000 n_{\rm ism}^{-1/3}$ yr. Such a short interval of time between a nova outburst in a cataclysmic binary and its reappearance as a dwarf nova is at the extreme end of the interval ($\sim 10^3$–10^6 yr) predicted by current evolutionary (hibernation) models of cataclysmic variables (e.g., Shara *et al.* 1986). While this time interval can be lengthened by relaxing the assumption of complete sweeping of the interstellar gas, the resulting increase in the radius of the nova remnant at a given expansion velocity becomes much too large for the ejected and swept-up shell to be significantly photoionized by the EUV and soft X-ray flux of SS Cyg. A more promising possibility is that the high-excitation absorption features in SS Cyg originate in a planetary nebula, since the expansion velocities of planetaries (25 ± 10 km s^{-1}; Pottasch 1984) are more naturally comparable to the expansion velocity of 20 ± 7 km s^{-1} implied by the blueshift of the high-excitation absorption features in SS Cyg. Although a similar origin has been suggested by Bode *et al.* (1987) for the extended far-infrared (*IRAS*) image of GK Per, given that the far-infrared image of SS Cyg does not appear to be extended and that the far-infrared (Jameson *et al.* 1987) and radio (Córdova, Mason, and Hjellming 1983) fluxes of this source are so small (<10 mJy, <8 mJy, and ≤0.10 mJy at 12 μm, 25 μm, and 6 cm, respectively), this scenario for the origin of the high-excitation absorption features of this cataclysmic variable appears to be excluded.

d) Bow Shock

An alternative possibility for the origin of the high-excitation absorption features in the spectrum of SS Cyg which is due to the interaction of the stellar wind with the interstellar medium involves the bow shock formed by the supersonic motion of this cataclysmic variable through the interstellar medium. If SS Cyg moves through the interstellar medium with a velocity of ~ 30 km s^{-1}, a weak bow shock is formed in front of the spherical region containing the stellar wind (the "wind zone") as a result of the supersonic motion of this structure through the interstellar medium. Although the velocity of this shock is too small to produce C IV or Si IV by collisional ionization, it may be large enough to compress the interstellar medium ionized by the EUV and soft X-ray flux of SS Cyg sufficiently to produce the required column densities of the high-excitation species in the interstellar gas behind the bow shock.

Due to the interest in bow shocks in Herbig-Haro objects, much work has been done recently on the characteristics of these structures (see Raga and Böhm 1985; Choe, Böhm, and Solf 1985). For our purposes, it is sufficient to note that, upon passage through the bow shock, the interstellar gas is deflected away from the moving body by an angle χ with respect to the symmetry axis. This deflection is due to the conservation of the parallel component of the velocity of the interstellar medium and the jump condition on the perpendicular component as the interstellar gas passes through the oblique shock. The expression for χ and for the jump condition ϵ can be found in Choe, Böhm, and Solf (1985). If the velocity of the moving body is at right angles to the line of sight with respect to the interstellar medium, the shocked interstellar gas acquires a velocity component $V_{\rm proj} = V_{\rm ism}(\cos^2 \phi + \epsilon^2 \sin^2 \phi)^{1/2} \sin \chi$ along the line of sight, where $V_{\rm ism}$ is the velocity of the cataclysmic variable with respect to the interstellar medium and ϕ is the angle between the tangential surface of the bow shock and the symmetry axis. This angle at a given impact parameter is given by the shape of the bow shock, which we take to be that given by Raga and Böhm (1985). This information, the assumption that we are viewing the bow shock from the side, that the adiabatic index of the ionized gas is $\gamma = 1$, and that the Mach number of the shock is $M = V_{\rm ism}/C = 2.5 T_4^{-1/2} \approx 2.5$ specifies the problem completely. Given these assumptions, $\phi = 34°$, $\epsilon = 0.51$, $\chi = 15°$, and $V_{\rm proj} = 7$ km s^{-1}. If the Mach number (and hence the velocity of the cataclysmic variable with respect to the interstellar medium) is twice as large, $M = 5$, $\phi = 28°$, $\epsilon = 0.18$, $\chi = 22°$, and $V_{\rm proj} = 20$ km s^{-1}. Consequently, if the column densities of the high-excitation species arise in the compressed region behind the bow shock, the velocity displacement of the high-excitation absorption features with respect to the low-excitation absorption features in the ultraviolet spectrum of SS Cyg is explained. To see if sufficiently large column densities can be produced, we write the column density of the X (C IV, Si IV, or Si III) ion as $N_X = A_X \xi_X f R_{\rm wz} n_2$, where $n_2 = M^2 \sin^2 \phi n_{\rm ism}$ is the number density of the shock-compressed interstellar gas and $fR_{\rm wz}$ is the projected thickness of the shock, which is parameterized as a fraction f of the radius of the wind zone $R_{\rm wz}$. The radius of the wind zone is given by the balance of the pressure of the stellar wind and interstellar gas: $\rho_{\rm wind} V_{\rm wind}^2 = \rho_{\rm ism} V_{\rm ism}^2$, which is $\langle \dot{M}_{\rm wind} \rangle V_{\rm wind}/4\pi R_{\rm wz}^2 = \mu n_{\rm ism} V_{\rm ism}^2$, where $\mu = 1.34 m_{\rm H}$ is the mean atomic mass. Taking as before $V_{\rm wind} = 5000$ km s^{-1} and $\langle \dot{M}_{\rm wind} \rangle = 2.5 \times 10^{-10}$ $M_\odot$ yr^{-1}, the radius of the wind zone is $R_{\rm wz} = 2 \times 10^{17} n_{\rm ism}^{-1/2} V_{\rm ism,30}^{-1}$ cm, where $V_{\rm ism,30}$ is the velocity of the cataclysmic variable with respect to the interstellar medium in units of 30 km s^{-1}. Collecting terms, the column density of the X ion is $N_X = 1 \times 10^{18} A_X \xi_X f n_{\rm ism}^{1/2} V_{\rm ism,30} \sin^2 \phi$ cm^{-2}. At a relative velocity of either 30 km s^{-1} or 60 km s^{-1}, $N_{\rm C\,IV} \approx 1 \times 10^{14} \xi_{\rm C\,IV} f n_{\rm ism}^{1/2}$ cm^{-2}, the column densities of Si IV and Si III are smaller by a factor of $10\xi_{\rm C\,IV}/\xi_{\rm Si\,IV}$ and $10\xi_{\rm C\,IV}/\xi_{\rm Si\,III}$, respectively, and ξ_X is an implicit (nonlinear) function of $n_{\rm ism}$ and $V_{\rm ism}$ through n_2 and $R_{\rm wz}$. Given this result, if both f and ξ_X were nearly equal to one, the column densities of C IV and S IV, but not Si III, observed in the direction of SS Cyg could be realized. In truth, however, f is likely to be much less than one; an upper limit can be set by assuming that the projected thickness of the shock is given by the distance between the bow shock and the surface of the wind zone, which implies $f \lesssim \frac{1}{3}$. The ionization fraction of C IV and Si IV are similarly likely to be significantly less than one. Assuming as before that the cataclysmic variable radiates with the spectrum of an optically thick accretion disk and boundary layer accreting at an effective rate of 2.5×10^{-9} $M_\odot$ yr^{-1}, we find that the ionization fraction ξ_X of C IV, Si IV, and Si III at a distance $R_{\rm wz}$ away from the cataclysmic variable is 0.23, 0.25, and 0.41, respectively, if $V_{\rm ism} = 30$ km s^{-1} and $n_{\rm ism} = 1$ cm^{-3}. These values for ξ_X change by only a small amount if the velocity of the cataclysmic variable with respect to the interstellar medium is doubled, because the resulting increase in the density of the shock-compressed gas is offset by a decrease in the radius of the wind zone. The same effect offsets an increase in the density of the upstream interstellar gas, although the square-root dependence of N_X on the density of the interstellar medium increases the column density of the various ions. No choice of ξ_X, f, and $n_{\rm ism}$ will, however, change the fact that the measured column density of C IV in the spectrum of SS Cyg is less than or equal to the column density of Si III, because the difference in the abundances of carbon and silicon implies that $\xi_{\rm Si\,III}/\xi_{\rm C\,IV} \gtrsim 10$ for the fixed path between the bow shock and the surface of the wind zone, and consequently that $\xi_{\rm C\,IV} \lesssim 0.1$. Given this result, we must conclude that the requisite column densities of the high-excitation species cannot be formed in the bow shock of a cataclysmic variable moving through the interstellar medium.

e) Thermal Conduction Interface

Last, it is possible that the high-excitation absorption features in the spectrum of SS Cyg are due to a thermal conduction interface between the million degree plasma of the local interstellar medium observed in soft X-rays (e.g., McCammon *et al.* 1983) and the largely neutral gas responsible for the low-excitation absorption features. Such an interface should have column densities like those predicted by the interstellar bubble model, so that the line of sight would have to intersect the interface nearly tangentially to account for the observed large column densities. Given such an orientation, however, it would be difficult to account for the 20 km s^{-1} velocity displacement of the high-excitation absorption features with respect to those of the neutral and singly ionized species.

V. IMPLICATIONS FOR THE CLOUD-FILLING FACTOR OF THE LOCAL INTERSTELLAR MEDIUM

An important aspect of the high-excitation absorption features produced in the photoionized region surrounding a cataclysmic variable, hot white dwarf, or early-type star is that they provide a probe of the gas density in the immediate vicinity of the exciting star, rather than an average of the gas density along the line of sight. Thus, the presence or absence of high-excitation features in the ultraviolet spectra of astronomical sources could be used to determine the filling factor of clouds in the interstellar medium. McKee and Ostriker (1977) predict that clouds fill roughly one-quarter of the interstellar volume, the remaining being filled by very hot, low density gas which is incapable of producing the observed high-excitation absorption features. If one considers only C IV and Si IV absorption features or only blueshifted C IV, Si IV, and Si III absorption features, our results are consistent with this prediction, in that one of the five cataclysmic variables we observed shows absorption by these high-excitation species, a result which is consistent with observations of hot white dwarfs, since two (Feige 24 [Dupree and Raymond 1982] and PG 1034+001 [Sion, Liebert, and Wesemael 1985]) of the 10 white dwarfs observed show high-excitation absorption features. However, if the unshifted Si III absorption features seen in V3885 Sgr, IX Vel, and (possibly) RW Sex are also formed in a circumstellar region of ionized gas, than a cloud-filling factor near unity is implied. If this conclusion is correct, and if the model of a photoionized circumstellar H II region is applied to these other sources, the lack of absorption by C IV and Si IV in their spectra indicates either that (1) the ambient interstellar density of these cataclysmic variables is less than that for SS Cyg or (2) the soft X-ray luminosity of these cataclysmic variables is insufficient to ionize a significant volume of gas in the interstellar medium. Alternately, since the Si III absorption features in V3885 Sgr, IX Vel, and RW Sex share the velocity of the interstellar absorption features, they might originate in $\sim 10^{4.5}$ K interstellar gas in the conduction interfaces and/or photoionized coronae of the intervening neutral clouds responsible for the neutral and singly ionized interstellar absorption features. While this possibility would restore the conclusion of a cloud-filling factor of $\sim 20\%$, it is not clear that sufficient column densities can be realized in this manner. Given the many parameters that determine the column densities of the high-excitation species: the unknown ambient interstellar densities, the poorly known EUV and soft X-ray spectra and luminosities of cataclysmic variables, the poorly known speeds and directions of the motions of cataclysmic variables through the interstellar gas, and many more, it would be premature to claim a measurement of the cloud-filling factor in the local interstellar medium based on our results.

VI. SUMMARY

Using high-resolution *IUE* spectra of five cataclysmic variables, we have presented a study of the interstellar medium in the vicinity of the Sun ($d \lesssim 150$ pc) which augments similar studies employing nearby hot white dwarfs. By means of the column densities of the neutral and singly ionized interstellar species, we have obtained values of the depletion of Si, Mg, Mn, and Fe that are in general agreement with the results of previous studies of the depletion of these elements as a function of mean interstellar hydrogen number density. In addition, the velocities of the absorption features of the neutral and singly-ionized interstellar species are found to be consistent with Lallement, Vidal-Madjar, and Ferlet's (1986) fits to the directions and velocities of the components of the local interstellar medium based on the optical absorption features of stars in the vicinity of the Sun. Moreover, these studies have supplied us with the column density of neutral hydrogen toward each of our program stars. As discussed in § III*a*, these hydrogen column densities are of particular importance in (1) constraining the soft X-ray luminosity of cataclysmic variables, (2) supplying us with some predictive power in deciding which cataclysmic variables are likely candidates for successful soft X-ray observations, and (3) supplying us with much smaller reddening values of cataclysmic variables than can typically be obtained by other methods.

In addition to supplying us with the parameters characterizing the interstellar medium in the vicinity of the Sun, these ultraviolet spectra also reveal velocity-shifted absorption features of C IV, Si IV, and Si III in the outburst and quiescence spectra of SS Cyg. We have shown that the observed column densities and velocity displacements of these high-excitation absorption features can be explained by an expanding H II region of interstellar gas photoionized by the EUV and soft X-ray flux of this cataclysmic variable *if* the number density of the interstellar medium in the immediate vicinity of SS Cyg is ~ 1 cm^{-3} and the luminosity of the soft X-ray component of the spectrum of SS Cyg is close to its theoretical value of $\sim 4 \times 10^{34}$ ergs s^{-1}. More exotic explanations involving an interstellar bubble, a circumbinary shell, the bow shock formed by the supersonic motion of SS Cyg through the interstellar medium, or a thermal conduction interface in the interstellar medium along the line of sight to SS Cyg, appear to be incapable of explaining the column densities and velocity displacements of the high-excitation species. In the context of the model of an expanding photoionized H II region, the lack of similar column densities and velocity displacements of the high-excitation species in V3885 Sgr, IX Vel, and RW Sex appears to indicate either that (1) the ambient interstellar density of these cataclysmic variables is less than that for SS Cyg or (2) the soft X-ray luminosity of these cataclysmic variables is insufficient to ionize a significant volume of interstellar gas. Concerning the first possibility, we have noted that a similar fraction (1 in 5) of hot white dwarfs and cataclysmic variables show interstellar absorption features of C IV, which indicates a similar filling factor of the higher density interstellar medium needed to produce observable column densities of the high-excitation species. Given small number statistics, however, little can be made of this speculation until data on a much larger sample of nearby hot white dwarfs and cataclysmic variables can be made available. Concerning the second possibility, given what little we know about the soft X-ray luminosities of V3885 Sgr, IX Vel, and RW Sex, and indeed of cataclysmic variables as a class, little can be concluded until more observations of cataclysmic variables at soft X-ray wavelengths are made available.

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