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THE EVOLUTION OF THE OPTICAL SPECTRUM OF THE DWARF NOVA SS CYGNI OVER ONE COMPLETE OUTBURST CYCLE[1]

JOHN T. CLARKE, DEBBIE CAPEL,[2] AND STUART BOWYER[3]
Space Sciences Laboratory, University of California
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ABSTRACT

Visible spectra covering 3900–5000 Å with a spectral resolution of ~6% of the full width of the quiescent emission lines have been obtained each night during one full outburst cycle of the dwarf nova SS Cygni. These spectra cover all phases of the outburst centered near 1983 August 1 and allow us to tabulate for the first time the sequence of pronounced spectral changes in the H and He lines and their phasing with respect to the continuum brightening, which covered a factor of roughly 50. The Balmer emission lines show a brief reduction in intensity lasting 1–2 days on the rise to outburst, then an increase (compared to their quiescent intensity) which occurs near the time of maximum light, and a pronounced narrowing which appears anticorrelated with the continuum flux. The He II λ4686 line, which is not detected at all in the quiescent spectrum, rises to a flux level comparable to the Balmer lines at the height of the outburst, is well correlated in intensity with the continuum flux, and may broaden with increasing flux (the opposite of the Balmer line behavior). The He I line at 4471 Å, although fainter than these other lines, appears to follow the general behavior of the Balmer lines rather than that of the He II line. The absorption component of the Balmer lines is measurable whenever the continuum level is sufficiently high to provide contrast between the absorption and outburst-narrowed emission components, and the apparently constant equivalent width of the Balmer absorption may always be present and simply be dominated by the strong emission lines in the quiescent spectrum. Modeling of the line emission distributions across the disk indicates that most if not all of the surface of the disk is ionized near maximum light, and the He II emission thus strengthens as the H I emission fades.

Subject headings: stars: accretion — stars: dwarf novae — stars: individual

I. INTRODUCTION

There have recently appeared several publications presenting theoretical models to explain the observed outbursts of dwarf novae as sudden brightenings of the accretion disk which arise quasi-periodically in a hysteresis cycle in the functional relationship between the viscosity and surface density of the disk. The models discussed by Bath and Pringle (1981, 1982) attribute the onset of the outburst to either changing viscosity in the disk or to a sudden increase in the rate of mass transfer from the companion star due to the presence of unstable ionization zones in that portion of the companion's atmosphere which is heated by radiation from the accretion disk. An alternative model discussed by Faulkner, Lin, and Papaloizou (1983) and Papaloizou, Lin, and Faulkner (1983) suggests that the outbursts can be triggered spontaneously at any point in the disk by a thermal instability which arises from opacity changes in regions of partial hydrogen ionization. Both models predict pronounced changes in the temperature and density distributions in the disk over the course of an outburst; in particular, the thermal instability model offers specific predictions of the extent of ionization of hydrogen as a function of both time and radial position in the disk. The observational tests applied to these models to date consist mainly of their ability to fit the numerous dwarf novae light curves compiled by amateur observers and of their ability to fit the continuum energy distributions measured at a few isolated stages of the outburst cycle (see references above). Unfortunately these comparisons test just the disk-averaged radiation properties and do not sample the structure of different regions in the disk, as is necessary to determine where and how the disk instability occurs.

In an earlier paper we presented limited observational data which illustrated the promise of a technique for "mapping" temperature and density changes in different parts of the accretion disk during an outburst by an analysis of the velocity distributions in the resonant emission lines (Clarke and Bowyer 1984). In moderately high resolution outburst spectra of both RX And and KT Per we detected a narrowing of the Balmer emission lines by roughly a factor of 2 from their quiescent widths, which implied a pronounced decrease in the line emission from the inner disk during outburst (assuming only that the lines are broadened predominantly by Keplerian rotation in the disk). A preliminary quantitative analysis of the changing widths of the lines suggested that sizable fractions of the inner portions of the disks were either thermally ionized, photoionized, or had collapsed onto the white dwarf. It was clear that a more extensive data set would be required to distinguish between these mechanisms. If the inner disk were photoionized, for example, the narrowing of the emission lines should appear correlated with the increase in ionizing continuum flux over the outburst cycle.

Ideally one would like to have a series of high-resolution spectra covering all phases of the same outburst from which to model the evolution of the line emission from different regions of the disk and thereby map the evolution of the disk through outburst. In practice this is difficult to accomplish, as dwarf novae outbursts are notoriously unpredictable on time scales

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[1] Based on observations at Lick Observatory.
[2] Also with Oxford University.
[3] Also with Department of Astronomy, University of California, Berkeley.

of days to weeks, and a relatively large telescope (implying limited observing time and advance scheduling) is required to obtain high resolution spectra of these systems in quiescence (the brightest systems are typically 12–14 mag). Our observing strategy to attempt to overcome these obstacles was to request two entire bright runs in mid-summer (the clear weather season in California), employ a grating blazed in the second order at the Cassegrain focus for maximum sensitivity and moderately high resolution, and take one spectrum each night of each of the half-dozen dwarf novae which were brightest and appeared most likely to erupt based on then current AAVSO light curves. Luck was with us in our first run, as the brightest dwarf nova available in the summer skies, SS Cygni, began a rise to outburst on our fifth night of observations, and had nearly returned to minimum light by the final night of that run. The observations of SS Cyg will be presented in § II; the observed line changes and their qualitative interpretation will be discussed in § III; and a geometric modeling of the accretion disk surface brightness distributions required to reproduce the observed emission line profiles will be presented in § IV. In § V we will present a list of the observational effects from this one outburst which a successful model for the outbursts of dwarf novae must explain.

II. OBSERVATIONS

The spectra in this paper were obtained over the nights of 1983 July 19 through August 5 and August 13 through August 22 on the 40″ Anna Nickel telescope of Lick Observatory. All spectra were collected at the Cassegrain focus, employing a 500 line mm^{-1} grating which was blazed at 7500 Å and provided 4 Å resolution in second order over the range 3900–5000 Å, and using the standard image dissector scanner detector. No spectra were obtained on Friday nights due to the use of the telescope in a summer visitors' program. All other spectra were obtained under photometric conditions with absolute flux scales derived from observations of the same two photometric standard stars each night. SS Cyg was observed to be at minimum light up to and including the night of July 24 and over the entire second run. No systematic variations in the shape or width of the resonant emission lines was observed over these periods, although some flickering in both continuum and line intensity at a level $\lesssim 30\%$ was present from night to night. To derive a high signal-to-noise ratio representative quiescent spectrum we have averaged all the spectra from the second run and plotted the result in Figures 1 and 4 (marked as 8/13–22/83). The other spectra covering the rise to and fall from maximum light (which occurred on the night of July 28) are plotted in Figures 1–4; these spectra were all obtained in 32 minute integrations except on the night of July 27, when a 72 minute integration was performed in an attempt to improve the measurement of the absorption line shapes. The dates listed in Figures 1–4 are for the universal times of the observations, and the Julian dates of these spectra are shown in Figure 5.

The observed qualitative character of dwarf novae spectra, which changes from broad resonant emission lines of H and He superposed on a blue continuum at quiescence to broad absorption lines occasionally filled in by emission cores at outburst, has been recognized for at least half a century (see discussion in Joy 1940). However, the evolution of these changes has never before been well observed due to the unpredictable nature of the outbursts. As discussed in § I, the value of the present observations is that they allow us to measure both the strengths and velocity distributions of the various resonance

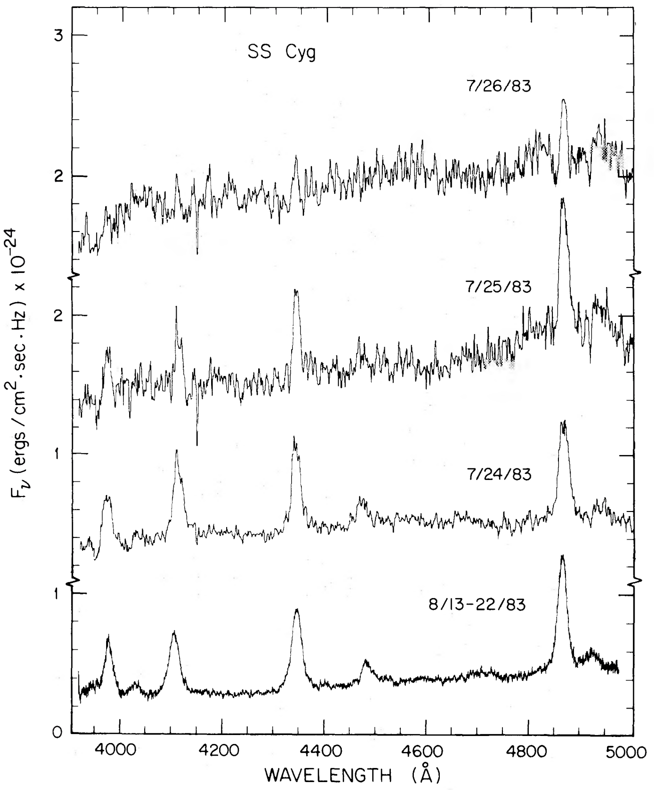

FIG. 1.—Individual nights' spectra obtained with the 40″ telescope at Lick Observatory of SS Cyg during the slow phase of the rise to outburst. The bottom spectrum is the average of 10 nights when SS Cyg was at quiesence, combined to improve the signal-to-noise ratio in the minimum spectrum.

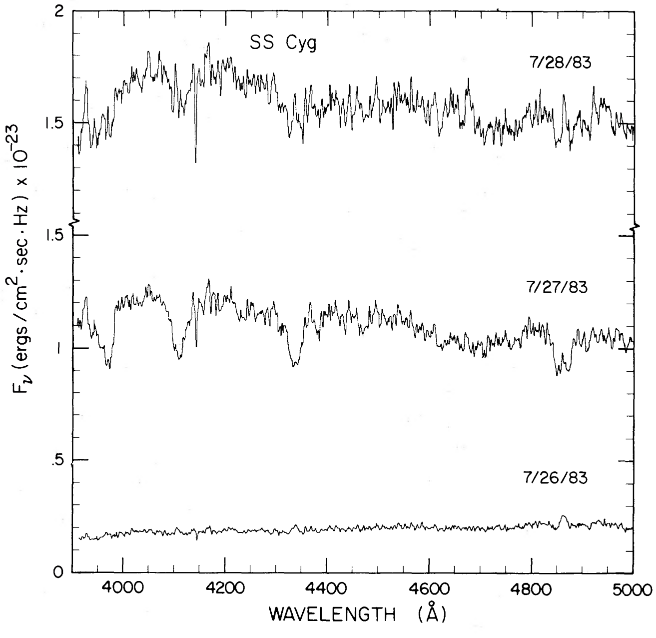

FIG. 2.—As in Fig. 1, but covering the fast rise phase of the outburst. The apparent absorption spike near 4140 Å is an artifact of the flat-fielding of the detector response.

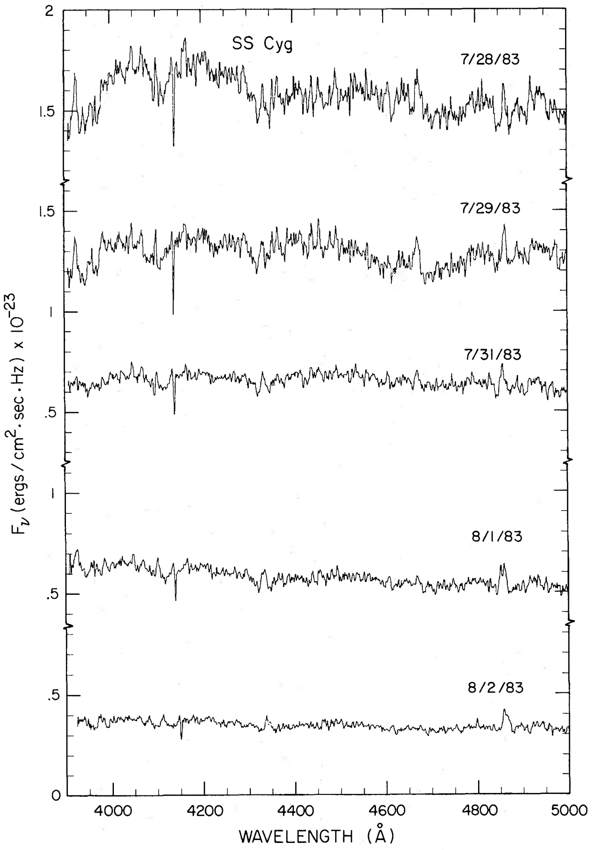

FIG. 3.—As in Fig. 1, but covering the first half of the decline from maximum light.

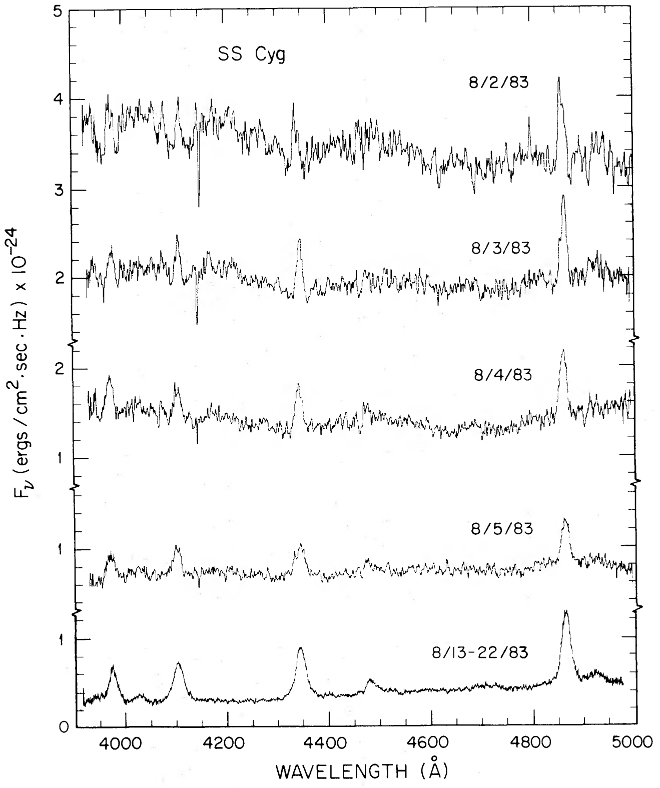

FIG. 4.—As in Fig. 1, but covering the second half of the decline from outburst.

lines and plot these against the continuum flux to study both the excitation mechanisms and the source regions of the different lines.

The results of our measurements of various parameters of the H and He lines are plotted in Figure 5. The 4600 Å continuum and He II λ4686 line properties plotted in the top three panels have been measured in the units indicated. The Balmer emission line properties plotted in the next two panels have been determined by averaging the Hβ, Hγ, and Hδ lines (which had been added in bins of equal velocity) to improve the signal-to-noise ratio in the line shapes. The Hϵ line was not included in this summation due to the presence of contaminating Ca II emission at overlapping wavelengths. These panels thus represent average Balmer line profiles and do not take into account either changes in the Balmer decrement with time or different values of the decrement at different velocities in the line profile. Furthermore, the line width measurement plotted is the full width at half-maximum (FWHM) of the averaged line profile, which indicates the width only at one point in the lines and does not indicate the changing shape of the Balmer lines: more detailed modeling of the Balmer line shapes will be presented in § IV.

III. SPECTRAL EVOLUTION

a) Continuum Light Curve

The observed line properties are all plotted in Figure 5 on the same time scale as the continuum flux at 4600 Å. The light curve of SS Cyg (covering all outbursts) has been faithfully recorded by the AAVSO since the late 1800s. Generally only the AAVSO has previously recorded the light curves on the rise to the outburst, and therefore there is some scatter ($\sim \pm 0.4$ mag) resulting both from contributions from different observers and flickering in the sources. In addition, the AAVSO light curves give visual magnitudes which include the changing flux in the very bright emission lines, whereas our 4600 Å continuum flux measurements are independent of the lines. It is apparent from Figure 5 that the rise to maximum light actually consisted of two discrete stages. There appeared first a linear increase by a factor of 2 per day lasting 3–5 days, followed by a much more rapid brightening by a factor of 8 in less than 2 days. The AAVSO light curves of this rise to outburst indicate that SS Cyg brightened by $1\frac{1}{2}$–2 mag over the night of July 27 alone (i.e. in less than about 8 hr).

There have been previous indications of a general reddening of the continuum spectrum during the rise to outburst of VW Hyi from ground-based and *IUE* spectra (Hassall *et al.* 1983) and more recently during a different outburst of SS Cyg from *Voyager* UVS spectra (Polidan and Holdberg 1984). (In addition, the observations reported by Polidan and Holberg 1984 and also by Panek and Holm 1984 of U Gem suggest that the disk is generally not as luminous in the far-ultraviolet [$\lambda > 912$ Å] as earlier models for the disk–white dwarf boundary layer predicted.) The observation of VW Hyi on the rise to outburst was made at a point where the visual continuum had increased by a factor of ~ 6 over the quiescent level and was a factor of ~ 8 below the peak of the outburst, while the FUV continuum showed little or no corresponding increase above the quiescent level. This level of visual brightening is consistent with the inflection point on the rise portion of our 4600 Å light curve in Figure 5. The narrow wavelength range of our spectra precludes very accurate measurements of the continuum shape during the observed outburst of SS Cyg; however, the contin-

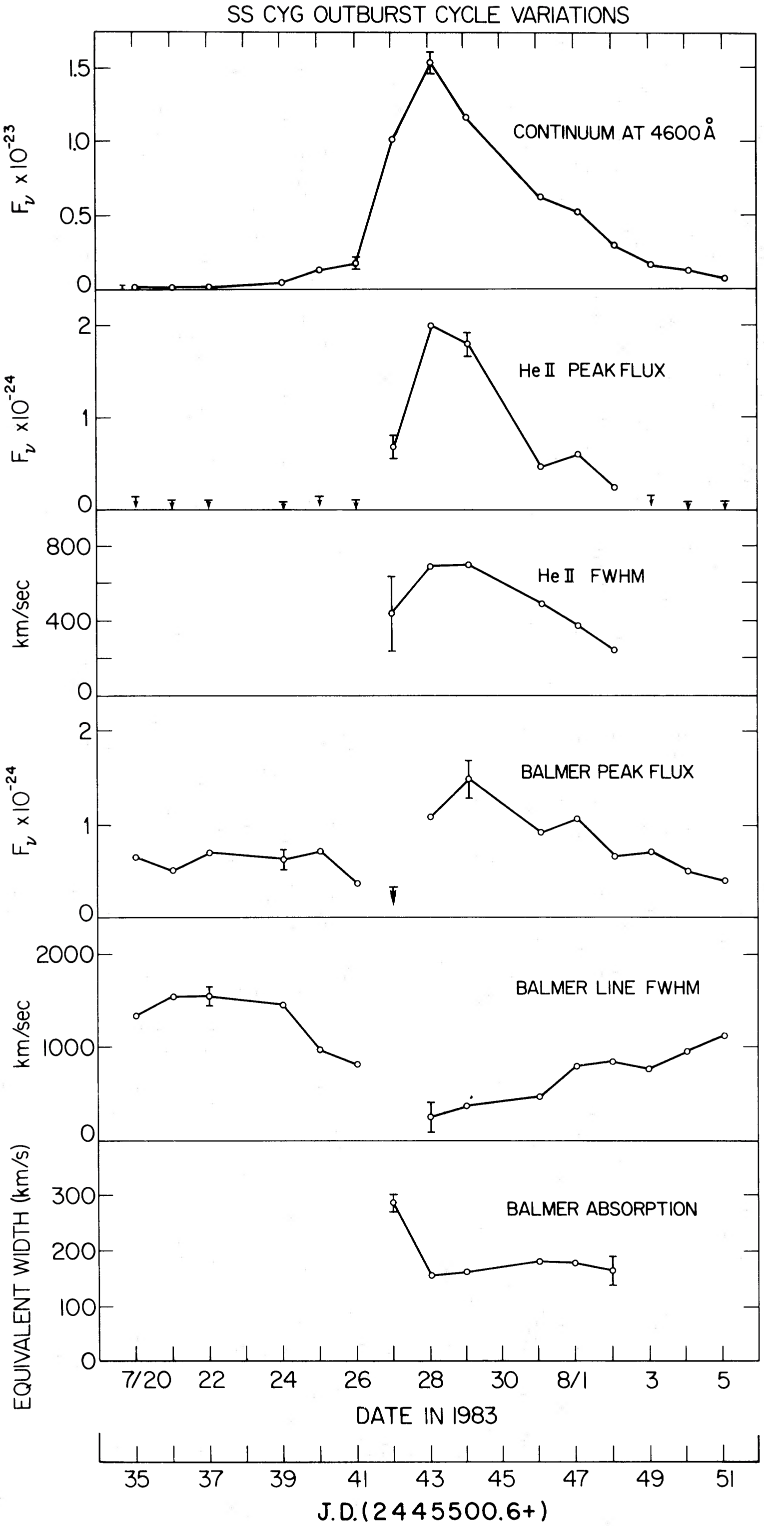

FIG. 5.—Various emission- and absorption-line parameters plotted on the same time scale as the monochromatic continuum flux at 4600 Å. See § III of the text for a detailed discussion.

uum was clearly bluer near maximum light on July 27 through July 29 than during quiescence, and also appeared markedly redder than the quiescent spectrum during the slow rise on the nights of July 25 and July 26. It is tempting to identify the slow rise phase of the outburst that we have observed with the initial red continuum rise reported by the other workers. In terms of the accretion disk instability models, the first, slower stage may represent the growth phase of the instability and the more rapid increase the response of the remaining disk to that instability. The existence of two discrete stages in the rise to outburst is an important point; although initial slow increases and declines just before the outbursts of different systems have been recorded previously in the AAVSO light curves (J. Mattei, 1984, personal communication), none of the models published to date predicts this effect. The continuum decline stage from July 28 on can be well fitted by a simple exponential decline with a $1/e$ folding time of 3.2 days.

b) Balmer Emission Lines

The development of the Balmer emission lines over the course of the outburst can be seen qualitatively in the individual spectra in Figures 1–4 and quantitatively in Figure 5. In Figure 1 it is apparent that the H lines were decreasing in flux as the continuum increased in the slow rise phase, the line profiles became narrower as the lines faded, and the Balmer decrement appeared relatively constant throughout this phase. During the fast rise phase of the continuum plotted in Figure 2, the H emission was virtually absent from the July 27 spectrum, but appeared 24 hours later in the absorption cores of the July 28 spectrum with a dramatically narrower line shape and a higher peak flux than in the quiescent spectrum. In the decline stage plotted in Figures 3 and 4 the H emission lines broadened steadily and the peak flux in the lines decreased without any strong variability from night to night as the continuum declined (corresponding to the disk cooling period of the accretion disk instability models). We did not detect any pronounced variations in the Balmer decrement over the course of the outburst, although the measurement errors of the weak, narrow emission lines near maximum light (cf. the night of July 27 plotted in Fig. 2) are rather large.

The peak flux and FWHM of the average of the Hβ, Hγ, and Hδ emission lines is plotted on the same time scale as the continuum flux in Figure 5. The dramatic narrowing of the lines indicates a substantial reduction in the emissivity of the high velocity material in the H line emitting region, as the wings of the lines completely disappeared during maximum light. Possible explanations for this decrease in high-velocity emission are collisional ionization of the neutral H, photoionization of the neutral H, or bulk removal of the high-velocity material (for example, by a collapse of the inner disk onto the white dwarf). Collapse of the disk can be ruled out, since the observed line behavior would require that all but the outermost edge of the disk collapsed in less than 2 days at a time when the continuum flux (which is believed to emanate from the disk) was increasing sharply. In addition, the peak flux in the center of the lines recovered within 1–2 days of the time of the fast rise, which would require an implausibly high rate of mass transfer to replenish the disk. Photoionization seems unlikely to dominate the H emission line changes, since the Balmer peak flux recovered immediately after the fast rise stage and reached maximum values during the following period of maximum light, when the *Voyager* observations indicate that the ionizing EUV continuum flux is generally also at a maximum (Polidan and Holberg 1984). There is also some indication, discussed in the previous section, that generally during the slow rise stage just the visible continuum and not the FUV continuum increases, whereas the Balmer lines grow both fainter and narrower over this time. The H line width does appear to have been generally anticorrelated with the continuum flux, however, suggesting that photoionization may play an important role in the inner, high velocity portion of the disk. We therefore conclude that the dominant mechanism leading to the pronounced reduction in H line emission during and especially on the rise toward outburst is collisional ionization of H due to increasing temperature in the line emitting region. Attributing the line emission to the surface of the accretion disk, the changing line profiles thus allow us to map which portions of the disk have been heated (or possibly irradiated) above the ionization point of neutral H over the course of the outburst (see § IV).

c) Balmer Absorption

The equivalent width (EW) of the Balmer absorption (also plotted as the average of the Hβ, Hγ, and Hδ lines in Fig. 5), which often appears prominently in the outburst spectra of dwarf novae, could only be measured accurately for SS Cyg in those spectra where (*a*) the H emission lines were sufficiently narrow and faint, and (*b*) the continuum flux was sufficiently strong to not obscure the absorption. Since the H emission lines narrowed with increasing continuum flux, we obtained good measurements of the Balmer absorption on the nights of July 27 (when it appeared most pronounced) through August 2. The relative absorption and emission strengths in these spectra were determined by simply fitting the points of inflection of the emission wings with the absorption core (cf. Fig. 3). We have presented independent evidence from quiescent and outburst spectra of RX And that the narrowing of the Balmer lines during outburst as measured from these points of inflection is not an artifact due to enhanced absorption (Clarke and Bowyer 1984), supporting the inflection point separation of the emission and absorption components. SS Cyg also has an observable secondary stellar component in its minimum spectrum which may contribute to the absorption, but since the Balmer lines are clearly dominated by emission at minimum and we further assume that the companion star does not brighten appreciably during outburst, this contribution is assumed to be negligible.

With the exception of the spectrum obtained on July 27, when the emission was especially weak and the absorption especially strong, the EW of the H absorption appeared constant at a value of 180 ± 10 km s^{-1} although the continuum flux decreased by a factor of 6 over the same interval. The implication of the apparent constancy of this absorption is that it may very well be present at all times in the spectrum of SS Cyg at an EW of 180 km s^{-1} and simply masked by much stronger emission in the quiescent spectrum. The belief that most of the continuum emission arises in the accretion disk and the observed flat-bottomed shape of the Balmer absorption lines suggest that most of the absorption occurs in the surface layers of the rapidly rotating disks, rather than in the white dwarf atmosphere. The white dwarf atmosphere is believed to be much less luminous in the continuum and the width of any absorption lines from the white dwarf atmosphere would be due to pressure broadening, which should yield the more sharply peaked absorption cores observed in the spectra of isolated white dwarfs. Herter *et al.* (1979) have applied stellar atmosphere theory to the surface of an α-model disk during outburst to simulate the observed Balmer line shapes by surface absorption of continuum emission emanating from within the disk. From a comparison of their modeled profile with the observed spectrum of CD $-42° + 4462$, Herter *et al.* (1979) concluded that there was evidence for pressure broadening in the Balmer absorption. Our spectra of RX And and KT Per (Clarke and Bowyer 1984) showed a reasonably good fit to Herter *et al.'s* (1979) modeled disk absorption profiles, however, and we feel that there is good evidence that much of the observed absorption arises in the disk itself.

Taking the other side, Panek and Holm (1984) have argued that the Lyα absorption observed from U Gem is linked to the white dwarf rather than the disk. In any event, the absorbing region must cover the continuum outburst region of the system since the EW of absorption is constant during decline, and the pronounced ionization changes in the H and He emission lines show that the disk and not just the white dwarf heats up considerably during outburst. If the absorption is indeed always present and only increases in strength during the fast rise to outburst, this finding has important implications for the structure of the line emitting region of the disk. It would require that this region be optically thick to the H lines in quiescence as well as in outburst and that the surface layer of relatively cool absorbing H be enhanced during the fast rise to outburst, perhaps due to an increased low-velocity wind from the surface of the disk. (There is independent evidence for a neutral hydrogen wind from the observation of Lyman series absorption from SS Cyg; Polidan and Holberg 1984). We wish to point out that the models of Herter *et al.* (1979) were for a steady disk with constant mass transfer and are therefore more applicable to the quiescent than the outburst spectrum of a dwarf nova, which supports the idea of disk absorption in the quiescent spectrum of SS Cyg.

The existence of a constant level of absorption will also affect the measurement of the emission line shapes due to the different underlying continuum than was previously assumed. Since the H emission line properties plotted in Figure 5 for the nights of July 28 through August 2 were determined from the points of inflection in the absorption core these data are not affected, and in most of the remaining spectra the continuum is sufficiently faint and the emission lines sufficiently strong that the effect is small. However, we wish to point out that some, but not all, of the decrease in both peak flux and FWHM of the Balmer emission lines observed in the slow rise stage (and especially on the night of July 26) may alternately be explained by an increasing underlying continuum with a more pronounced intensity of absorption (if the absorption has constant EW) which obscures part of the emission lines.

d) He II *λ4686 Emission*

As shown in the two panels in Figure 5 this line exhibited markedly different behavior over the course of the outburst than the Balmer emission lines. He II was not detected in any of the quiescent spectra, and the upper limit to the possible peak flux at 4686 Å derived from the high signal-to-noise ratio composite spectrum in our second run (labeled 8/13–22/83 in Fig. 4) is on the order of 5×10^{-26} ergs cm^{-2} s^{-1} Hz^{-1}, which is a factor of 40 below the highest value observed on the night of July 28. In fact, the He II flux over the course of the outburst appears to have been very well correlated within the continuum flux at 4600 Å, suggesting that the same conditions which power the continuum rise lead to ionization of neutral He and/or excitation of the He II emission. The correlation of He II flux with continuum flux in the outburst of SS Cyg suggests that the excitation of the line is due either to (*i*) photoionization and excitation by EUV photons which increase in intensity with roughly the same time dependence as the visible continuum, or (*ii*) collisional ionization and excitation due to the increasing temperature of the disk during the outburst. Potential excitation mechanisms for He II λ4686 have been reviewed recently by MacAlpine (1981) for the physical conditions likely to be present in the line emitting clouds of active galactic nuclei, which may be similar to the conditions in dwarf novae accretion disks. The radiation mechanisms likely to produce λ4686 emission (which corresponds to a transition from $n = 4$ to $n = 3$ in He II) are (*a*) ionization of He I by EUV continuum radiation (with $h\nu = 4$ Rydbergs or $\lambda \lesssim 230$ Å) and subsequent radiative recombination, (*b*) direct excitation by the EUV continuum populating the $n = 4$ level, or (*c*) pumping of the $n = 4$ level by absorption of HLyα emission. The third mechanism exploits the near-coincidence of HLyα (1215.67 Å) with the $n = 2$ to $n = 4$ line of He II (1215.19 Å). Since both lines are broadened by at least several hundred km s^{-1} at all stages of the outburst the two lines will overlap almost completely, but unfortunately the strength of the HLyα emission in dwarf novae accretion disks in general has never been determined observationally and is quite uncertain theoretically. The many published soft X-ray fluxes and IUE spectra of dwarf novae suggest that there is likely to be sufficient EUV flux to power processes (*a*) and (*b*), and scaling from the efficiency of the H Lyα pumping process calculated for QSOs by MacAlpine suggests that this process may also be important *if* the λ4686 emitting region is subject to the same continuum and line fluxes which are observed from Earth. The main difficulty in calculating the efficiency of these three processes is that this requires knowing the location of the λ4686 emitting region and further assuming an incident flux and optical depth at all relevant wavelengths for each process. Since the geometry and physical conditions of the λ4686 emitting region are still quite uncertain we will not pursue this question further. Collisional excitation of He II by thermal electrons also appears very likely to contribute strongly to the observed λ4686 emission. If the continuum increase plotted at the top of Figure 5 is considered as a σT^4 increase in bolometric luminosity, then the observed increased excitation of He II appears to follow very well the increase in temperature in the accretion disk.

IV. MODELING OF THE EMISSION LINES

In modeling the observed emission line profiles with accretion disk brightness distributions it has been our goal to make as few assumptions as possible about the physical structure of the disk. Rather it has been our intention to model the net emissivity of the disk as a function of radial distance (i.e., velocity); these radial emissivity profiles can then be used to constrain models for the disk structure. The two fundamental assumptions made are that the line emission (with the possible exception of a central component to be discussed later) comes from the accretion disk and that the width of the lines is due predominantly to Doppler broadening from Keplerian rotation of the disk. The latter assumption is equivalent to assuming that the turbulent kinetic energy is much less than the rotational kinetic energy, which requires that the turbulence be subsonic ($\alpha < 1$). The interpretation of the width of the Balmer lines as representing Doppler broadening from the rotation of the disk is a common assumption, and has been convincingly demonstrated to work for the Balmer emission from DQ Her in an observation and modeling of the line profile changes during an eclipse of the accretion disk by the companion star (Young and Schneider 1980). Evidence has also been presented for an additional low-velocity component of the Balmer emission of undetermined origin in spectra of HT Cas (Young, Schneider, and Schectman 1981), UX UMa (Schlegel, Honeycutt, and Kaitchuck 1983), and RW Tri (Kaitchuck, Honeycutt, and Schlegel 1983). However, the bulk of the emissive flux appears to be consistent with simple Keplerian rotation in an accretion disk confined within the Roche lobe of the white dwarf. It should be noted that the He II $\lambda 4686$ emission line seems to arise from a different source region than the Balmer lines in virtually every system that has been studied in detail (i.e., by radial velocity curves, eclipse profile changes, etc.). This is, of course, not surprising, as He II emission requires a substantially higher level of excitation than H I emission.

One secondary assumption has also been made which affects only our modeling of the outer regions of the disk. Earlier models of accretion disks have assumed that the disk is optically thin to line emission and have always produced line profiles which are double peaked due to the toroidal geometry of the disk (see for examples Smak 1981 and Tylenda 1981). By contrast, the observed lines from SS Cyg are *always* single peaked and the observation of a seemingly constant equivalent width of Balmer absorption suggests that the disk in SS Cyg must be optically thick in the lines. We therefore assume in our model that the disk is everywhere optically thick in the lines and point out that comparisons with the published profiles of Smak (1981) yield similarly shaped double-peaked profiles if we exclude our treatment of the outer edge of the disk described below.

It is therefore necessary to add a low velocity component to "fill in" the center of the lines to match the observed profiles, and there are indications that this filling component may have a different source region than the rest of the line emission. We have chosen to parameterize this component as the outer edge of a flared, optically thick disk which has the same velocity and surface emissivity as the outermost annular ring on the surface of the disk. The validity of this parameterization requires that the outer edge of the disk be optically thick in the lines, so that its emission brightness is proportional to its apparent surface area rather than to the volume of material contained. One result of our modeling is that the observed lines can be well fitted by the addition of a disk rim corresponding to a flaring of ± 0.04–0.07 of the outer radius of the disk. We stress, however, that the actual location of this low-velocity emission region is not yet well established.

Our modeling is accomplished by separating the disk into a series of concentric rings and further separating each ring into azimuthal sections, whose brightness per unit area is assumed to obey a radial dependence of the form $f(r) \propto r^{-\alpha}$ (this is required to match the broad wings of the observed lines). Numerical integrations in the azimuthal and radial directions are then performed, with the line-of-sight rotational velocity of each section determined both by its position in the disk [the functional relationships are $v(r) \propto r^{-(1/2)}$ and $v(\theta) \propto v \sin \theta$, where θ is the angle from the line of sight chord through the center of the disk) and the inclination of the whole system ($v \sin i$). System parameters for SS Cyg have been taken from Kiplinger (1979) and are $i = 30°$, $P = 0.2762$ days, $M_{WD} = 1.07$ $M_{\odot}$, and $M_C = 0.80$ $M_{\odot}$. Following these integrations a running triangular filter of 250 km s^{-1} FWHM was passed over the output line profile to simulate the resolution of the spectrograph. Since the maximum radial velocity observed in the emission lines from SS Cyg is less than 100 km s^{-1} (Kiplinger 1979), smearing of the observed line profiles over the length of our 32–72 minute integrations is considered to be negligible. The model thus has four parameters which can be varied to fit the observed line profiles: the inner and outer radii of the line emitting portion of the disk, the quantity α in the radial brightness function, and the thickness of the disk rim (i.e., the magnitude of the filling component). Initially the only constraint placed on the possible values of these parameters was that R_{outer} must be less than the mean white dwarf Roche lobe radius (~ 0.7 $R_{\odot}$).

The errors in the determinations of these four parameters have been assessed by the technique shown in Figure 6. The plotted emission line is the average of the three Balmer lines from the quiescent spectrum labeled 8/13–22/83 in Figure 4. We have first derived a best fit model profile to this line (obtained with values $R_{\mathrm{in}} = 0.01$ $R_{\odot}$, $R_{\mathrm{out}} = 0.40$ $R_{\odot}$, $\alpha = 1.40$, edge $= 0.08$ $R_{\odot}$) and then varied each parameter independently with the other three held constant to test the sensitivity of the fitting process to each parameter. It can be seen from Figure 6 that each parameter affects a different portion of the line profile. However, R_{in} and the edge size can be constrained much more exactly than the other two parameters since they alone determine the shapes of the outermost and innermost portions of the line profile, respectively. R_{in} generally determines the high-velocity cutoff (where the line wings go to zero), and the edge size determines the degree of peaking in the center of the line. R_{out} and α are somewhat redundant, so that although they can be distinguished, the accompanying uncertainties are much greater, especially in the case of R_{out}.

V. RESULTS OF THE MODELING

Armed with this technique we have modeled the sum of the Balmer lines in the quiescent (1983 Aug 13–22) and individual nights' spectra plus the average He II $\lambda 4686$ line profile from the nights of 1983 July 28–31, and plotted the model fits in Figure 7. The fitting of the base of the Balmer emission lines to the points of inflection with the absorption core has been discussed in § III*c*, and we believe that this is not a significant source of error in our modeling. The variation of the four parameters over the course of the observed outburst of SS Cyg is plotted in Figure 8, with the error bars determined by the technique shown in Figure 6.

Generally R_{out} was not well constrained by this modeling at any point in the outburst cycle: it is consistent with any value in the range $0.10 < R_{\mathrm{out}} < R_{\mathrm{Roche\ lobe}}$. Applying the additional constraint that R_{out} be greater than R_{in} requires R_{out} to be larger than ~ 0.6 $R_{\odot}$ over the nights of 1983 July 29–31, and this is essentially all that can be determined from the modeling about R_{out}. Paczyński (1977) has calculated the expected dynamical extent of the individual disk particle orbits within the white dwarf Roche lobe. His results indicate that our assumption of a circular disk should be reasonably accurate (i.e., there should be little bulging of the disk toward the companion star) and from his Table 2, assuming $\mu = 0.43$ for SS Cyg, we derive an effective mean outer radius of the disk of 0.54 $R_{\odot}$. Lubov and Shu (1975), on the other hand, have estimated that the outer limiting radius of the disk should be substantially less than this based on gas dynamic calculations of the disk structure. Our modeling results as they stand are consis-

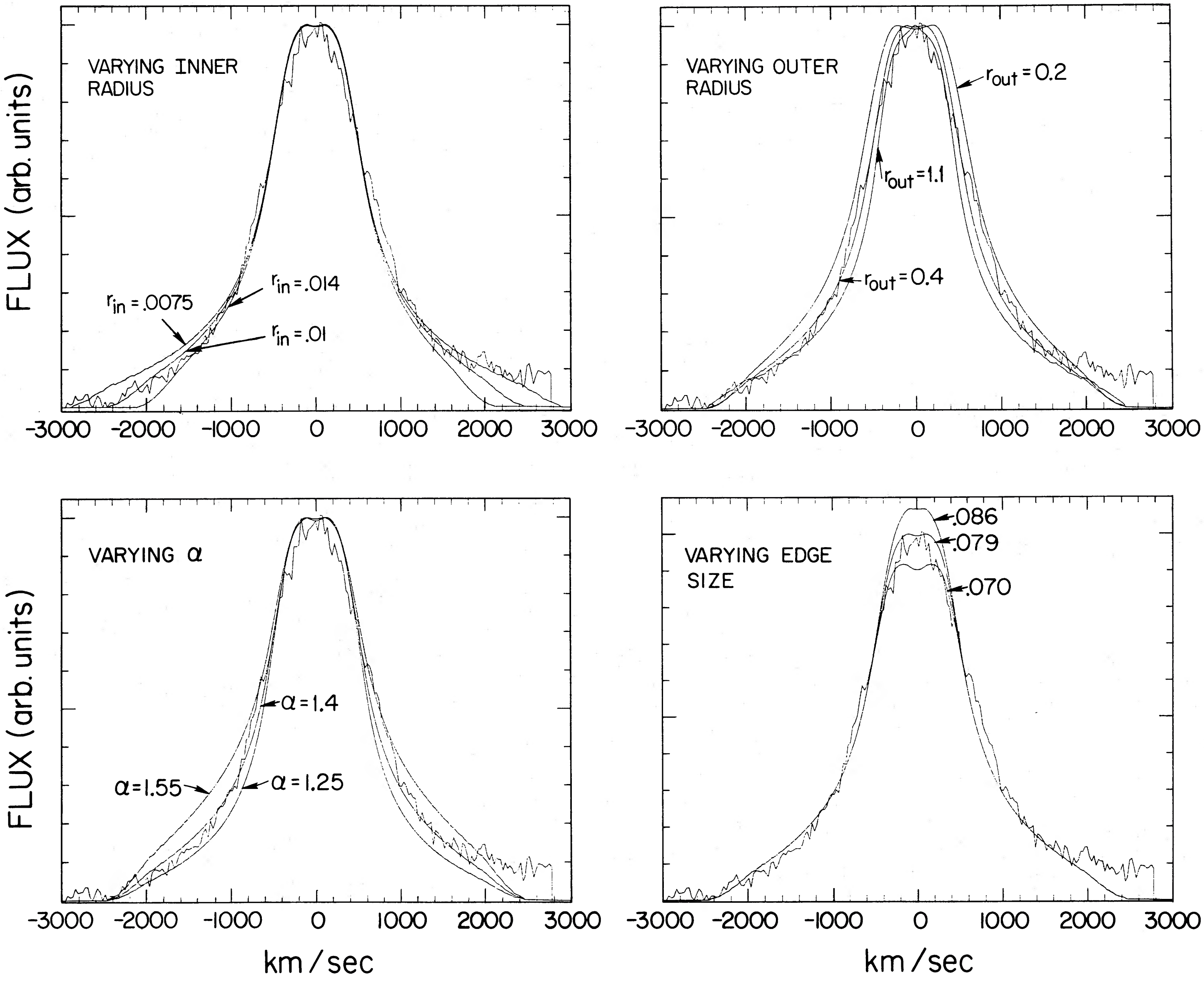

FIG. 6.—Model fits to the sum of three Balmer lines in the spectrum obtained 1983 August 13–22. In each panel one of the four variables in the model has been changed with the other three held constant to show the sensitivity of the modeling to changes in each variable.

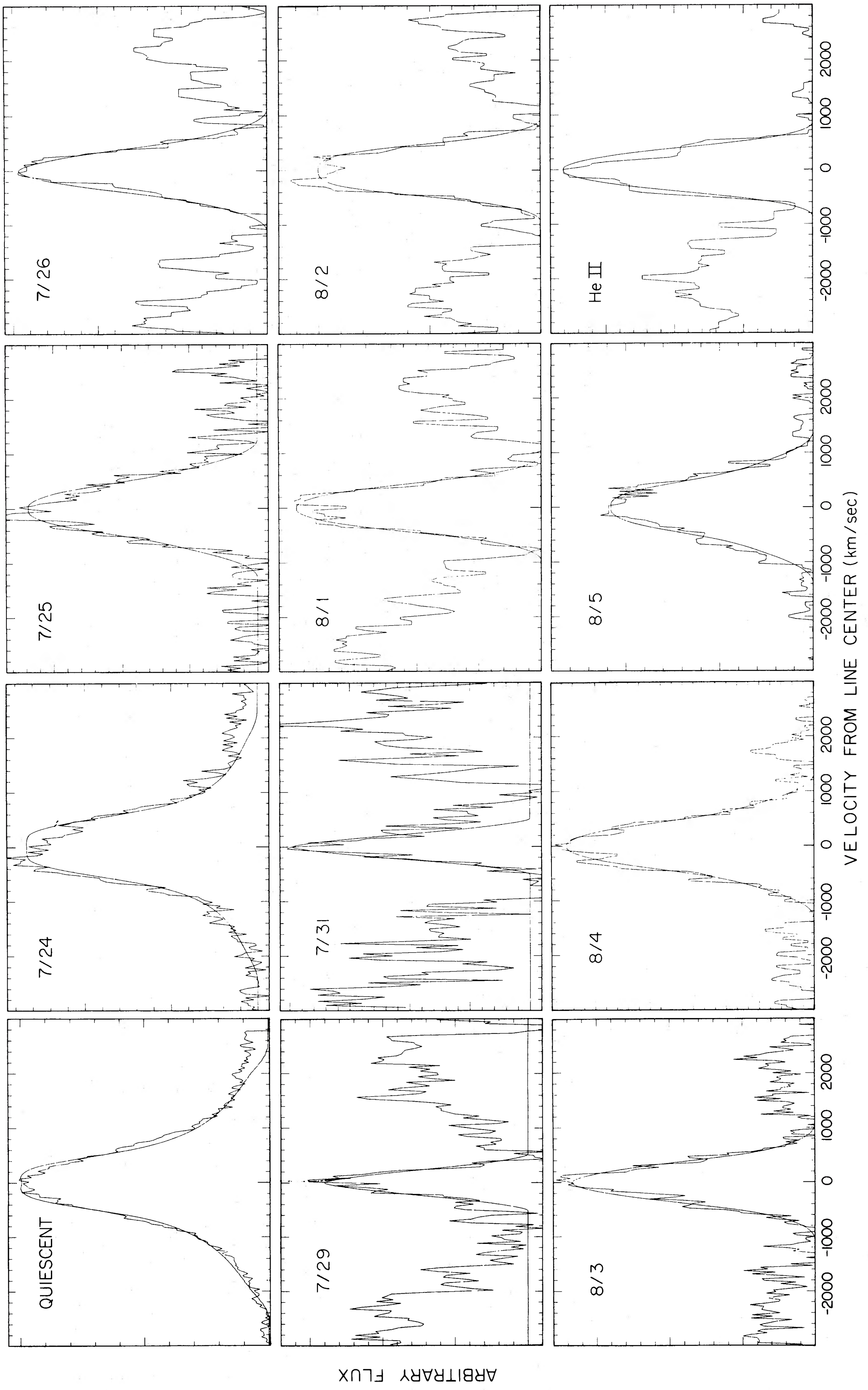

FIG. 7.—Model fits to the individual nights' Balmer emission lines and the average He II λ4686 line

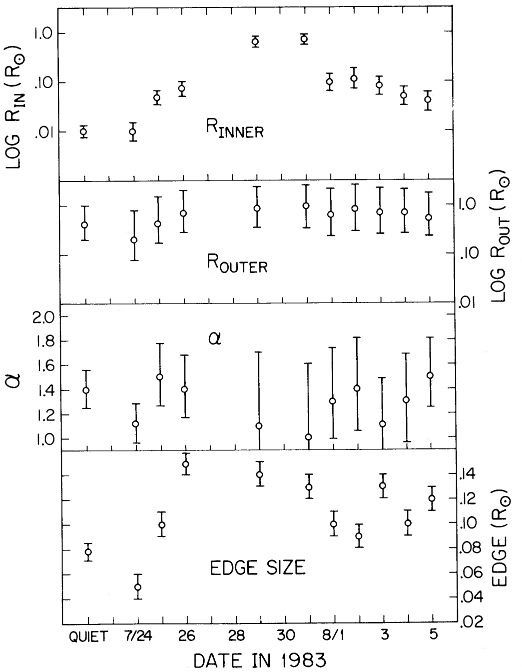

FIG. 8.—Best fit values for the four model parameters applied to the H emission lines over the course of the outburst. Uncertainties have been determined as shown in Fig. 6 and described in the text.

tent with Paczyński's results, but to match Lubov and Shu's results we would have to assume that the disk H is completely ionized at the time of maximum light and that the central filling component of the lines comes not from the disk rim but from some completely different portion of the system.

The modeled values for α become increasingly less accurate as the lines become narrower, since they are then determined by a more narrow radial section of the disk. The modeled results for α are therefore consistent with a constant value measured in quiescence of $1.2 < \alpha < 1.6$, although much less well constrained at maximum light (see Fig. 8). It is encouraging to note that Young and Schneider (1980) derived a value $\alpha = 1.0$ in modeling the Balmer lines from DQ Her and that Young, Schneider, and Shectman (1981) obtained $\alpha = 1.5$ for the Balmer lines in HT Cas, which are fairly consistent with our modeling of SS Cyg. Some recent theoretical models of the line emitting region have attributed the Balmer lines to the outer, relatively cool regions of the disk which are optically thin to the continuum (Williams 1980; Tylenda 1981). By contrast, the more direct modeling of observed line profiles presented here and referenced for DQ Her and HT Cas require that the line emissivity must increase considerably toward the center of the disk, and our estimate of R_{in} for SS Cyg in quiescence implies that the emissive region extends down nearly to the surface of the white dwarf. For comparison, this would require a mass transfer rate of $\lesssim 10^{-12}\ M_\odot\ \text{year}^{-1}$ in the model of Williams (1980), which certainly seems too low to power the observed disk luminosity and repeated outbursts.

The best determined of the four free parameters is R_{in}, which is measured directly from the point of inflection of the line wings with the continuum. R_{in} increases during maximum light by nearly two orders of magnitude, and this increase is well determined in addition to being quite pronounced. We have already interpreted this effect as representing ionization of neutral H in the disk in the more detailed discussion in § III*b*, and we can now quantify the effect by noting that the modeled values for the inner radius of the neutral H increase from $\sim 0.01\ R_\odot$ in quiescence to $\sim 0.6\ R_\odot$ near maximum light. The obvious conclusion is that either the entire disk becomes ionized near maximum light or that all but the outermost shell of the disk becomes ionized, which is required by our use of the disk edges as the low-velocity filling component. The quiescent R_{in} of 0.01 $R_\odot$ is just larger than the 1.07 $M_\odot$ white dwarf radius of 0.007 $R_\odot$ (Hamada and Salpeter 1961), implying that the line emitting portion of the disk extends nearly down to the white dwarf surface. We note further that the photoionizing flux at $\lambda < 912$ Å should be quite strong in the innermost disk, yet our modeling suggests that the quiet disk possesses a relatively cool (i.e., un-ionized) surface nearly all the way down to its inner edge at the white dwarf boundary layer.

The contribution of the low-velocity filling component which we refer to as the edge size is fairly well determined in our modeling and is seen to increase substantially around the time of maximum light. It is interesting that the fastest increase in edge size (by a net factor of 2 or 3) occurs during the slow rise phase of the outburst on the nights of July 24–26 (however, this is tempered by the same warning given in the last sentence in § III*c*). After July 26 the edge size appears to slowly decrease, but returns to its quiescent level much more slowly than either the continuum flux or the inner radius. The explanation which we prefer for this low-velocity component is that it arises from recombination in an extended cloud about the disk, providing low-velocity line emission which is never completely eclipsed when the rest of the disk passes behind the companion star, and which would not be completely ionized when the disk heats up during outburst. The increase over July 24–26 then may represent additional material leaving the disk as the disk heats up, the enhanced emission after about July 26 is due to recombination in the cloud as the disk cools, and the slowness of the decline is due to the weak gravitational binding of this material to the disk.

Finally, even though much less is known about the He II $\lambda 4686$ source region than about the Balmer lines, we have run our model on the summed He II profile from the nights of July 28–31 and plotted the result in Figure 7. The best fit values are $R_{\text{in}} = 0.14\ R_\odot$, $R_{\text{out}} = 0.5\ R_\odot$, $\alpha = 1.5$, and edge size $= 0.12\ R_\odot$. This gives the He II emission a similar outer radius, radial slope, and filling component as the Balmer lines, but the inner radius of the He II emitting region is substantially further out than the inner radius of the H lines in quiescence. In addition, the region of the disk giving rise to the He II emission extends to much smaller radii than the H I emission region near maximum light.

VI. SUMMARY OF RESULTS

A brief summary of these observations is given here in the form of observed phenomena which a successful model for the outbursts of dwarf novae (or, at least, for the outbursts of SS Cyg) must explain:

1. The monochromatic continuum flux increases in two discrete stages with very different rise times and total magnitude changes, although it is not clear that the slow rise stage is always present.
2. The H emission peak flux decreases significantly during the fast rise to outburst, then returns near maximum light with about twice its quiescent strength, and decays thereafter on a

time scale similar to that of the continuum decay. Modeling of the as yet mysterious low-velocity filling component of these lines shows that it decays much more slowly than the rest of the disk.

3. The pronounced narrowing of the H emission lines near maximum light indicates that most, if not all, of the disk H is ionized near maximum light, and the time scale for the lines to broaden after maximum light is similar to that of the continuum decrease. By contrast, the quiescent H emission must extend nearly down to the surface of the white dwarf.

4. The equivalent width of the H absorption appeared constant while the continuum decreased by a factor of 6 after maximum light, but this absorption was about twice as strong during the fast rise stage. The constant level of absorption may always be present, requiring that the disk be optically thick in the H lines.

He II emission was absent from the quiescent spectrum with a stringent upper limit but brightened in very good agreement with the visible continuum to appear strongly near maximum light. Both photo- and thermal electron excitation appear roughly capable of producing this emission, and we note that this line does not appear to extend nearly as far down toward the surface of the white dwarf as the H emission in quiescence.

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STUART BOWYER: Space Sciences Laboratory, University of California, Berkeley, CA 94720

DEBBIE CAPEL: St. Hugh's College, Oxford OX2 6LE, England

JOHN T. CLARKE: Code ES62, Space Sciences Laboratory, NASA/Marshall Space Flight Center, Huntsville, AL 35812