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THE NATURE OF THE RECURRENT NOVA T CORONAE BOREALIS: ULTRAVIOLET EVIDENCE FOR A WHITE DWARF ACCRETOR[1]

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ABSTRACT

We present the results of eleven years of observations of T CrB obtained with the *International Ultraviolet Explorer* (*IUE*). The *IUE* spectra show a rather complex structure in which emission lines and shell-like absorption features are superposed on a relatively hot and variable continuum. The reddening-corrected energy distribution can be represented by a single power-law spectrum $F_\lambda \propto \lambda^{-\alpha}$, with an average value $\langle\alpha\rangle = 1.26$. The changes in the UV continuum show no correlation with either the orbital phase or the optical variations. The changes in the UV emission lines (which, in addition to the lines commonly observed in ex-novae, e.g., N V, C IV, and He II, also include strong intercombination transitions, e.g., N IV] λ1486, N III] λ1750, Si III] λ1892, and C III] λ1908) are clearly correlated with the variations of the UV continuum, an indication that photoionization is the main energy input mechanism, as in most symbiotic stars. High-resolution spectra, although partially underexposed, show that the C IV λ1550 and He II λ1640 lines have very broad and shallow profiles with HWZI > 1300 km s^{-1}.

T CrB has been considered the prototype of non–TNR (thermonuclear runaway) recurrent novae in which the explosion is caused by the dissipation of the kinetic energy of a burst of matter accreted by a main-sequence star. However, all evidences from our *IUE* observations made during its quiescent state point toward a white dwarf as the hot component in the system, in particular (1) the fact that the bulk of the luminosity is emitted in the UV (average $L_{UV} = 40\ L_\odot$, peak $L_{UV} = 70\ L_\odot$) with little or no contribution to the optical; (2) the presence of strong He II and N V emission lines, suggesting temperatures of the order of 10^5 K; and (3) the rotational broadening of the high-excitation lines. These UV indications, together with the detection of T CrB in X-rays, and the presence of flickering in the optical light curve at several epochs, find a natural explanation in terms of accretion onto a white dwarf. With this assumption, from the observed UV luminosity we derive an average accretion rate of 1.5×10^{18} g s^{-1}. The luminosity of the He II λ1640 line (7×10^{32} ergs s^{-1}) has been used to provide an alternative estimate of the mass accretion rate and an estimate of the EUV–soft X-ray luminosity. The results are in agreement with those based on the UV continuum and on the theoretical expectations for a white dwarf accretor.

We show also that there is no contradiction between the assumption of a white dwarf and the historical records on the spectral and photometric behavior of T CrB at the time of the 1946 outburst. An interpretation of the outburst in terms of a TNR on a (massive) WD is supported by the following facts: (1) the spectral evolution during outburst has followed the same pattern generally observed in very fast novae; (2) the photometric light curve has obeyed the same relation M_v^{max}-t_3 followed by classical novae; (3) the luminosity at maximum was super-Eddington, a distinctive signature of a TNR model. The fact that the mass accretion rate during quiescence is very high and is exactly that required by the theoretical models to produce a TNR with the observed recurrence time on a massive WD supports this interpretation. The presence of the secondary maximum in the outburst light curve, a feature generally not observed in classical novae, is interpreted as the conversion into the optical of the UV radiation from the hot nova remnant, by the optically thick, low-temperature shell observed at the time of the secondary maximum. The spectral evolution after outburst also suggests a rather low mass for the ejected envelope, as expected for a TNR in a massive white dwarf.

The most serious difficulty for our interpretation in favor of the presence of a white dwarf comes from the results of a radial velocity study which indicated for the hot component of the system a mass higher than the Chandrasekhar limit. We point out, however, that the uncertainties and the difficulties involved in the measurements are such that a solution compatible with the presence of a massive white dwarf is within the observational errors.

Subject headings: stars: individual (T Coronae Borealis) — stars: novae — stars: white dwarfs — ultraviolet: spectra

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1. INTRODUCTION

T CrB is a member of the class of recurrent novae, a small group of objects whose precise nature is still controversial. A common property of recurrent novae (RNs) is the presence of more than one historical outburst in their light curve, with an amplitude of about 8–9 mag and recurrence times of a few tens of years. Their behavior is therefore intermediate between that of classical novae and dwarf novae.

Recently, Webbink et al. (1987, hereafter WLTO) have identified two subclasses of recurrent novae on the basis of their outburst mechanism: those powered by thermonuclear runaway (TNR) on a white dwarf and those powered by the transfer of a burst of matter from a red giant onto a main sequence star. One of the results of WLTO's study (based also on previous models and observations) was the interpretation of the behavior of the outburst of T CrB in terms of this second mechanism.

In this article, we present the results of 11 years (from 1979 to 1989) of observations of T CrB with the *IUE* satellite. The main conclusion of this study is that the overall behavior of T Crb in the UV and in other spectral ranges can find a natural and self-consistent interpretation in terms of accretion onto a white dwarf and of a TNR powered outburst.

2. T CORONAE BOREALIS: PREVIOUS OBSERVATIONS AND MODELS

T CrB is a double-line spectroscopic binary, with period $P = 227^{\rm d}.6$ (Kraft 1958; Paczyński 1965; Kenyon & Garcia 1986; Lines, Lines, & McFaul 1988), containing an M3 giant and a hotter companion whose nature has been so far rather elusive. The companion is responsible for the hydrogen Balmer emissions and other emission lines, and for the variable hot continuum that are superposed over the M-type spectrum which dominates the optical region during quiescence. Because of these features, T CrB can also be classified as a symbiotic star. The classification as recurrent nova is based on the occurrence of two historical outbursts in 1866 and 1946, during which the star has suddenly risen from a quiescent magnitude fainter than 9.5 to mag 2 and 3, respectively. During the two outbursts the photometric and spectroscopic behaviors were impressively similar (Pettit 1946b; McLaughlin 1946), a clear indication of the sameness of the physical processes responsible for the explosions. Expansion velocities of up to -5000 km s^{-1} have been seen in the hydrogen Balmer lines near the 1946 maximum (Sandford 1946: McLaughlin 1946; Herbig & Neubauer 1946). The extremely fast initial rise in the light curve was followed by a rapid decline with $t_3 \sim 5^{\rm d}.5$ (Pettit 1946a). A peculiar characteristic of the light curve was that, in both outbursts, the principal maximum ($V \sim 2.8$–3) was followed by a secondary maximum ($V \sim 8.5$), the time separation between the principal and secondary maximum being the same in the two cases ($\sim 100^{\rm d}$; Pettit 1946b, c).

The radial velocity data (Kraft 1958), revised by Paczyński (1965), suggest that $M_{\rm giant} > 2.2\ M_\odot$ and $M_{\rm hot} > 1.6\ M_\odot$, although these values might be affected by the uncertainties in the determination of $K_2 = v_2 \sin i$. In a recent study, Kenyon & Garcia (1986) have substantially confirmed the K_1 value, without attempting, however, to redetermine K_2, whose measurement is made quite difficult by the composite structure of the hydrogen emissions.

Rapid variations in the U light have been first reported by Walker (1957). The star was reobserved several years later by Walker (1977), who detected a U flickering with a time scale shorter than 15 s and variations of about 0.5 mag from the mean level. Bianchini & Middleditch (1976) found comparable U flickering at nearly the same epoch, but they reported a marked absence of such activity for 1976. Similarly, Oskanyan (1983) reported rapid variations in the U light curve in 1982 March and April and absence in June.

Córdova, Mason, & Nelson (1981), using the IPC detector on board the Einstein satellite, have detected a 0.2–4 keV X-ray emission from T CrB in 1979 February, corresponding to a luminosity of about 5×10^{31} ergs s^{-1}.

As a consequence of the radial velocity observations of Kraft (1958) and Paczyński (1965), which indicated that the secondary was more massive than 1.4 $M_\odot$, thermonuclear runaway models for the outbursts of T CrB were not taken into consideration. After the study by Paczyński & Sienkiewicz (1972) who found that Roche lobe overflow from a giant with deep convective envelope could lead to extremely high mass accretion rates $\dot{M}$ on a very short dynamical time scale, Plavec, Ulrich, & Polidan (1973) suggested that T CrB was in a rapid phase of convective mass loss and that the outburst was caused by the interaction between the mass-accreting star and the large amount of material falling on it. The two historical outbursts were therefore attributed to two episodes of extremely high mass transfer triggered by some instability of the red giant.

Webbink (1976) has considered in greater detail the outburst behavior of T CrB and has also interpreted the 1946 outburst in terms of episodic accretion phenomena from a giant onto a main-sequence star. He suggested that the outburst was caused by the transfer of a burst of matter ejected by the giant and by the subsequent dissipation of the excess energy of the transferred mass ($\sim 5 \times 10^{-4}\ M_\odot$) when its originally eccentric orbit around the secondary is made circular dynamically by supersonic collisions within the orbiting material, thus producing a ring. The secondary maximum, instead, is produced when the inner edge of the disk (produced by the broadening of the ring by viscous dissipation) strikes the surface of the (main-sequence) accreting star. With this model Webbink was able to explain the presence of the two maxima in the light curves, the time interval between them, and their relative amplitudes.

Additional considerations in favor of an accretion event onto a main-sequence star as responsible for the outburst of T CrB were reported in the extensive study on the nature of recurrent novae by WLTO. Following Webbink (1976), Livio, Truran, & Webbink (1986), and Starrfield, Sparks, & Truran (1985), WLTO considered, in general, both accretion events onto main-sequence stars and TNRs on white dwarfs as possible mechanisms for the outbursts of RNs. The accretion model requires dynamical phenomena, similar to those proposed by Webbink (1976) to reproduce the very rapid rise of the light curve in outburst, a shock-type events to produce the very high excitation coronal lines observed during decline. TNR models require a very massive, low-luminosity white dwarf and a very high accretion rate during quiescence ($> 1.7 \times 10^{-8}\ M_\odot$ yr^{-1}) to produce TNR outbursts with the short recurrence times scales compatible with those observed in RNs (< 100 yr). Under the above conditions, an accreted envelope mass as low as $5 \times 10^{-7}\ M_\odot$ (much smaller than in normal classical novae, $\sim 10^{-4}$ to $10^{-5}\ M_\odot$) is sufficient to trigger a TNR (Starrfield, Sparks, & Truran 1985). For more details about these models see also Livio (1988) and Kenyon (1988a).

WLTO have also established some general criteria and some identifying characteristics by which accretion-powered and TNR–powered RNs can be recognized even from a single outburst:

1. In TNR RNs, the luminosity at maximum is $L_{max} \geq L_{Edd}$.
2. In TNR RNs the high $\dot{M}$ ($>10^{-8}\ M_{\odot}\ yr^{-1}$) required to replenish the envelope of the WD on the short recurrence time scale implies that TNR RNs are bright UV sources (both in continuum and emission lines) at minimum light ($L \sim 100\ L_{\odot}$).
3. TNR models of RNs require a very massive WD ($M \sim 1.4\ M_{\odot}$) and a less massive ejected envelope (10^{-6} to $10^{-7}\ M_{\odot}$) than in classical novae. As a consequence, TNR RNs are emission-line objects at maximum.

WLTO have used these criteria and other considerations to give additional arguments against a TNR as the cause of the outburst of T CrB. Other considerations on the behavior of T CrB in quiescence and in outburst can be found in Kenyon (1988b).

Studies based on *IUE* spectra of T CrB have been presented by Krautter et al. (1981), Sahade, Brandi, & Fontenla (1984), Kenyon & Webbink (1984), and Kenyon & Garcia (1986). Kenyon & Webbink (1984) have made an attempt to fit the form of the continuum flux distribution to their synthetic UV continua but were unable to find a consistent model in light of the variability. Their conclusion was that accretion disks around a white dwarf or a main-sequence star could not give consistent explanation for the UV continuum of T CrB as a function of time. Kenyon & Garcia (1986), excluded the presence of a white dwarf on the basis of the relatively flat UV continuum they observed and of the overall weakness of the high-excitation lines. They tentatively ascribed the observed UV variations to fluctuations within an optically thin disk orbiting a main-sequence star and fueled by matter steaming from a lobe-filling M3 giant star at a rate of $10^{-6}\ M_{\odot}\ yr^{-1}$.

3. THE UV OBSERVATIONS

3.1. *The Data and the Phases*

T CrB has been monitored at both high and low resolution from the European *IUE* ground station of Villafranca del Castillo, Spain (VILSPA) from the early phases of *IUE*'s life until very recently. Preliminary results on our previous monitoring in the UV have been presented by Cassatella et al. (1982), Cassatella, Gimozzi, & Selvelli (1985, 1986), Gilmozzi, Selvelli, & Cassatella (1987, 1990) and Selvelli, Cassatella, & Gilmozzi (1989). For details about the *IUE* telescope and instrumentation, see Boggess et al. (1978). Dates and image numbers of the low-resolution observations are reported in Table 1, which also includes the corresponding visual magnitudes from the Fine Error Sensor (FES) on board *IUE* and the orbital phases. The ephemerides are those given by Kraft (1958) as revised by Paczyński (1985) and Kenyon & Garcia (1986), adopting T_0 = JD 2,435,687.6 (conjunction with hot star in front) and $P = 227^{d}.53$. In this convention, any effects due to a possible eclipse of the hot component are expected near phase 0.5. It should be noted that some confusion is present as to the setting of T_0: Kenyon & Garcia (1986) assume phase 0 when the red giant is in front; Kenyon & Webbink (1984) use the same phases as Paczyński but state that at phase 0 the cool star is in front; Palmer & Africano (1982) assume phase 0 on JD 2,402,734 (phase 0.22 in the convention used here); Walker (1977) gives phase 0.02 on JD 2,442,578 (phase 0.29); etc.

TABLE 1

DATES AND IMAGE NUMBERS OF LOW-RESOLUTION OBSERVATIONS

Date	Phase	SWP	LW[a]	F_{UV}[b]	α	m_{FES}
1979 Jan 5	0.00	3815	3395	6.39	1.3	10.13
1979 Mar 21	0.35	4750	4082	1.33	.7	9.91
1979 Jul 10	0.82	5759	4995	2.19	1.3	9.75
1979 Jul 15	0.84	5803/4	5053	2.31	1.3	9.78
1979 Aug 3	0.92	6062	5248	3.67	.9	10.07
1980 Jun 8	0.29	9228	7989	6.60	1.3	9.87
1981 Feb 17	0.40	13330	9929	9.29	1.3	9.96
1981 Dec 15	0.73	15762	12154	6.38	1.1	9.77
1982 Jun 3	0.47	17104	13392	6.14	1.1	10.02
1983 May 1[c]	0.93	19869	16145	13.3	.9	9.86
1983 Aug 22	0.43	20744	16640	5.58	1.3	10.00
1984 Apr 28	0.53	22867	3233	10.5	1.1	10.02
1984 Oct 2	0.22	24104	4484	8.07	1.1	9.73
1985 Mar 9	0.91	25401	5477	8.37	1.1	9.93
1985 May 2	0.14	25834	5881	5.77	1.1	9.82
1986 Jan 22	0.31	27556	7546	5.28	1.3	9.80
1986 Jul 19	0.10	28716	8658	6.79	1.4	9.95
1987 Jun 3	0.50	31095	10902	11.7	2.2	9.90
1988 Feb 24	0.67	32973	12730	6.94	1.7	9.87
1989 Mar 2	0.30	35648	15125	1.57	.9	9.86
1989 Apr 8	0.47	35959	15321	3.02	1.9	10.07
1989 May 21	0.65	36313	15562	3.92	1.9	9.94
1989 Jul 4	0.85	36611	15848	1.02	1.0	9.97
1989 Aug 1	0.97	36774	16038	0.69	1.1	10.15
1990 Feb 9	0.82	38170	17326	4.39	1.1	9.79

NOTES.—All fluxes are reddening corrected for $E_{B-V} = 0.15$.
[a] The numbers refer to LWR until 1983 Aug 22, to LWP afterward.
[b] $F_{UV} = \int_{1250}^{3200} F_{\lambda}\,d\lambda$, in 10^{-10} ergs cm^{-2} s^{-1}.
[c] The date for the LWR 16145 image was 1983 Jun 13.

3.2. *The UV Continuum Energy Distribution*

The *IUE* data of T CrB reveal a rather complex spectral structure in which both emission lines and shell-like absorption features are overimposed on a relatively hot continuum.

The UV continuum shows a broad interstellar dust absorption feature around 2175 Å compatible with $E_{B-V} = 0.15$ (Cassatella et al. 1982). As shown in Figure 1, the reddening-corrected continuum energy distribution is strongly variable and can be represented, at the various epochs, by a single power-law spectrum $F(\lambda) = A\lambda^{-\alpha}$ over the entire *IUE* range. In previous works (Krautter 1981; Sahade et al. 1984) the same reddening correction has been applied, but the continuum had been fitted with either a 27,000 K blackbody or with a Kurucz model stellar atmosphere distribution. In our spectra, the UV spectral index α ranges from 0.7 (1979 March 21) to 2.2 (1987 June 3), with a mean value of 1.26.

Table 1 lists for each spectrum the values of the reddening corrected integrated UV flux (1250–3200 Å), and of the index α. In general, when the flux is high, the continuum becomes steeper. In some cases, and especially in spectra in which strong "shell" absorption lines were present (see § 3.4), the determination of α was made difficult by the rather uncertain positioning of the continuum level. We estimate that the values of α listed in Table 1 are in general affected by an uncertainty of ± 0.2, with the exception of the value of 1981 February 17, where the estimated error was larger (± 0.3). The continuum of 1985 March 9 showed an "excess" at short wavelengths and was fitted with two components: $\alpha = 3.0$ shortward of 1450 Å, and $\alpha = 1.1$ at longer wavelengths.

The flattest spectrum ($\alpha \sim 0.7$) corresponds to the UV minimum of 1979 March. At the time of the other deep minimum in mid-1989 the slope of the UV continuum did not change significantly ($\alpha \sim 1.0 - 1.1$) with respect to the mean.

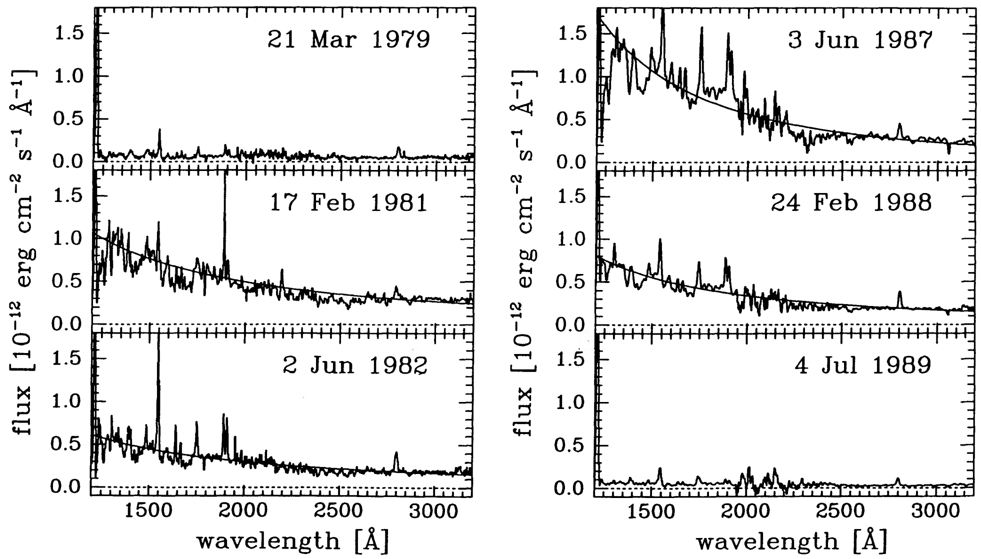

FIG. 1.—Time variability of the UV energy distribution of T CrB. A reddening correction corresponding to $E_{B-V} = 0.15$ has been applied. The two panels show typical spectra for the periods 1979–1982 (*left*) and 1987–1989 (*right*). In these periods the largest variations were observed in the UV. The spectra of 1979 March and 1989 July correspond to the deepest minima of the UV light curve, while the spectra of 1981 February and 1987 June correspond to relative maxima. Power-law fittings are superposed to the individual spectra (*continuous lines*).

A Balmer recombination continuum (peaking around 2800–3200 Å in the *IUE* range) is present in T CrB (Kenyon & Garcia 1986) and could in principle affect the shape of the *IUE* continuum, causing the derived power-law index to appear flatter, at least when the object is weak. However, as discussed in § 4.3 and shown in Figure 2, the Balmer emission does not substantially affect the continuum luminosity at long wavelengths. In addition, the index α mainly depends on the slope of the continuum at shorter wavelengths (< 1600 Å).

The changes in the UV continuum show no obvious dependence on the orbital phase (Fig. 3, *bottom*) and are due to intrinsic variations in the hot component. The absence of any (minor) modulation with phase could be ascribed either to the limited number of points and/or to the uneven sampling in time of the *IUE* observations. The UV variations do not show either any modulation with the "residual" photometric period of 55 days reported by Lines et al. (1988), which is prominent in the ground *U*.

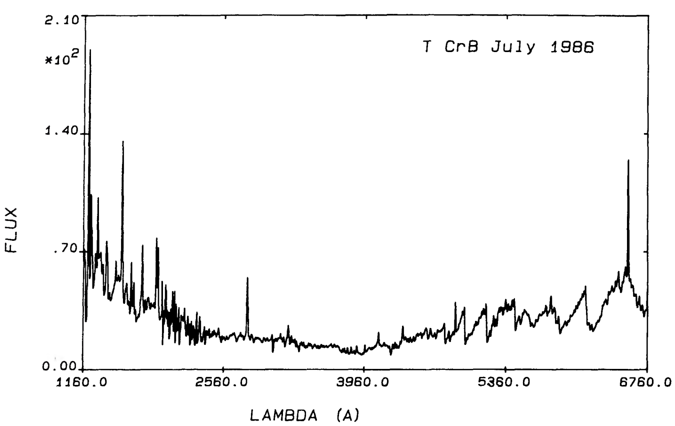

FIG. 2.—Reddening-corrected ultraviolet-to-optical spectrum of T CrB obtained in 1986 July (Cassatella et al. 1992). Fluxes are in units of 10^{-14} ergs $cm^{-2}\,s^{-1}\,A^{-1}$.

The deepest minimum (1989 August 1) and the highest maximum (1983 May 1) occurred at similar phases (0.97 and 0.93, respectively). Occultation effects are expected near phase 0.50 (red giant in front) if the inclination is higher than 68°. However, neither at phase 0.50 (1987 June 3), nor at phase 0.53 (1984 April 28), any flux decrease was observed. On the contrary, in both cases a very high continuum intensity was recorded.

In spite of the strong changes in the UV, there is poor indication of correlated variations in the optical from the nearly simultaneous FES photometry. At the times of the three UV maxima of 1983 May 1, 1987 June 3, and 1984 April 28, the FES magnitudes were 9.86, 9.90, and 10.02, while at the time of the UV minima of 1979 July and 1989 March 2, the FES magnitudes were 9.77 and 9.86. Only on 1989 August 1 is an m_{FES} minimum associated to a UV minimum. The UV maximum of 1983 May 1 almost agrees with the *V* and *B* maxima reported by Lines et al. (1988) in their Figure 2 (Peel 1991), but the U maximum occurs about 10 days later. Oskanyan (1983) and Lines et al. (1988) have reported that a strong decrease in brightness in all the observed (*ubv*) bands, together with a drop in the rapid variation in the *u* band occurred sometime between 1982 April 2 and June 8. *IUE* observations made on 1982 June 3 indicate, instead, a value close to the average for the continuum flux.

Figure 3 (*top*) shows the optical (FES) magnitude of T CrB as a function of the orbital phase: unlike in the UV, a very clear sinusoidal modulation is present, which can be totally accounted for by the rotation of the giant as its Roche lobe–filling shape presents a larger or smaller area according to the phase (and so the minima appear at phases 0 and 0.5, when the visible area is smallest). An orbital modulation of the light curve from visual and photographic estimates was already reported by Bailey (1975) and Peel (1985).

The lack of correlation between the strong variations in the UV and those in the optical (FES) is a clear indication that these changes have origin in different regions (namely the hot component and the giant) and will provide (see below) one of

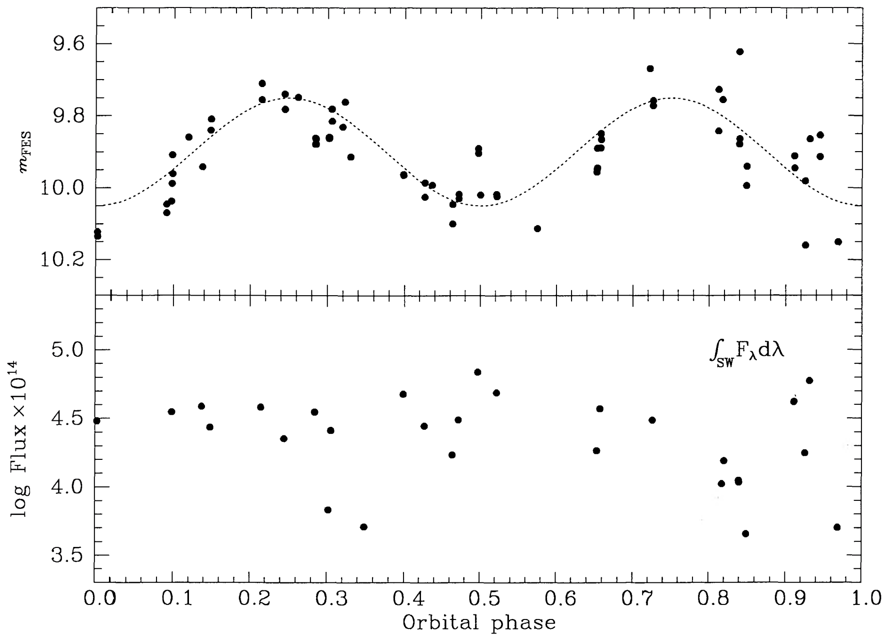

FIG. 3.—*Top:* Optical magnitudes of T CrB derived from the Fine Error Sensor on board *IUE* as a function of phase. The dotted sinusoid is not a fit but rather an indication of the expected effect of ellipsoidal variations in the red giant. *Bottom:* The integrated SWP flux (in ergs cm^{-2} s^{-1}) as a function of phase. Note the absence of any obvious variations connected to the orbital period.

the arguments in favor of the presence of a white dwarf in the T CrB system.

3.3. *The Emission Lines*

The UV emission lines in T CrB are remarkably intense compared to classical novae in quiescence. In addition to lines from N V, C IV, and He II, also seen in classical novae in quiescence, strong intercombination transitions (e.g., Si III], C III]) are present (see Fig. 4). N V, which is always present in T CrB, is detected only in the high-excitation old novae and is absent, for example, in V603 Aql.

The emission lines observed in the UV spectrum of T CrB are listed in Table 2, and the reddening-corrected fluxes of the strongest lines are given in Table 3. Most lines are straightforwardly identified and are typical also of symbiotic stars; however, for some lines (e.g., λλ1280, 1580, 1596, 1731, 1778, 1871, 2994, 3163), the identification is doubtful. Most of these lines are present also in the symbiotic nova RR Tel (Penston et al. 1983). The line around 1594 Å is also present in RW Hyd (Kafatos, Michalitsianos, & Hobbs 1980; Michalitsianos & Kafatos 1984), in Mira B (Reimers & Cassatella 1985) and in NGC 4151 (Ulrich et al. 1985). The 1283 Å emission is present also in VV Cep (Hagen et al. 1980). The O III Bowen fluorescence lines at 2839, 3047, and 3132 Å are occasionally quite strong. Figure 5 shows the time variability of the UV continuum intensity and of the strongest emission lines, respectively. Although the emission lines intensities *and* their measurements are affected by the presence of a variable shell absorption component (this is especially evident in the peculiar spectrum of 1981 February [see Fig. 4] in which all emissions but Si III] 1892 decreased while the continuum increased), it is clear that, in general, the variations of the emission lines, both of low and high degree of ionization, are correlated with the continuum variations. This suggests that photoionization by a variable hot continuum is the main energy input mechanism, as in the symbiotic stars AG Dra (Viotti et al. 1983), Z And (Fernandez-Castro et al. 1988), and BF Cyg (Gonzalez-Riestra, Cassatella, & Fernandez-Castro 1990).

The UV emission lines, like the continuum, do not show any dependence on the orbital phase. The general lack of significant changes in the line fluxes near phase 0.5 confirms the

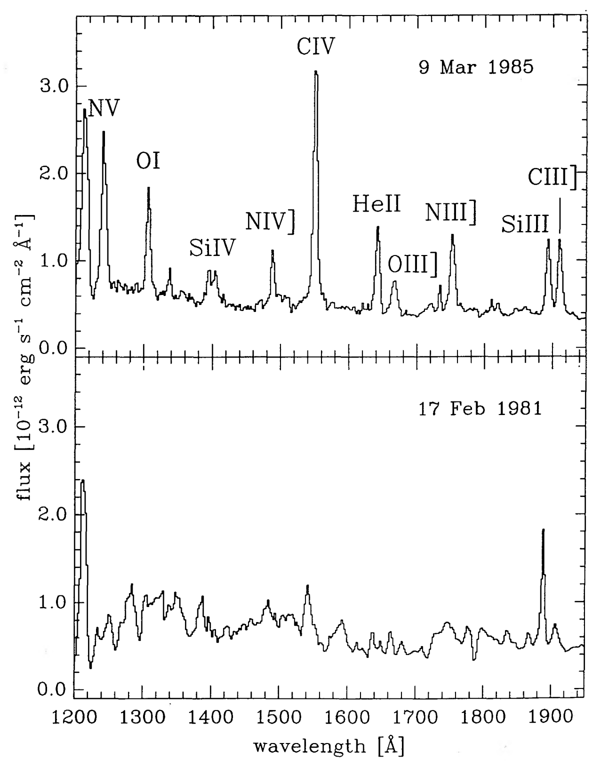

FIG. 4.—*Top:* Typical emission-line spectrum of T CrB, as observed on 1985 March 9. The most prominent emission lines are indicated. *Bottom:* Typical absorption-line spectrum of T CrB, as observed on 1981 February 17.

TABLE 2

LINES OBSERVED IN UV SPECTRUM OF T CORONAE BOREALIS

λ(Å)	Identification
	Emission Lines
1176	C III (4)
1240	N V (1)
1280	C I (5), (6), (7) (?)
1304	O I (2)
1335	C II (1)
1357	O I] (1)
1397	Si IV (1)
1486	N IV] (0.01)
1550	C IV (1)
1580	[Ne V] 1575 (?)
1596	[Ne IV] 1601 (?)
1640	He II (12)
1664	O III]
1731	Unidentified—also in RR Tel at 1728.91 and 1732.18 (see Penston et al. 1983)
1750	N III] (0.01)
1778	Unidentified—also in RR Tel at 1776.56
1812	Si II (1)
1871	O III 1872.78 (?)–also in RR Tel
1892	Si III] (1)
1909	C III] (0.01)
2296	C III (8)
2328	C II] (0.01) + Si II (0.01)
2385	He II (Pδ)
2447	[Ne IV] 2440 (?) + O IV (?)
2735	He II (Pβ)
2800	Mg II (1)
2836	O III (Bowen)
2994	Unidentified—also in RR Tel
3047	O III (Bowen)
3132	O III (Bowen)
3163	Unidentified
3188	He I (opt. 3)
3202	He II (Pα)
	Absorption Lines
1193	Si III (1) + Si II (5) + S III (1)
1262	Si II (4) + Fe II (9)
1298	Ni II (8), (9) + Fe II (K.)
1413	Si III (9) + Fe II (47), (69)
1432	Fe II (K.)
1466	Ni II (6) + Fe II (193)
1503	Ni II (7)
1535	Si II (2) + Ni II (K.)
1567	Fe II (44), (45) + Ni II (K.)
1628	Fe II (8), (43) + Ni II (K.)
1656	Fe II (42), (68)
1657	Fe II (40), (41)
1692	Fe II (38), (41), (85)
1719	Fe II (38), (39), (84) + Ni II (K.)
1775	Fe II (99) + Ni II (3)
1828	Fe II (65), (66)
1848	Fe II (98), (141)

NOTE.—Fe II (K.) and Ni II (K.) indicate strong lines reported in the line list by Kurucz 1988.

absence of eclipses (even partial ones) of the hot component (which would be most readily detected in the emission lines because of their origin in a larger region than the continuum). O I and N V are the emissions which show the largest variations with respect to the continuum. The O I (2) triplet was very strong at several epochs (e.g., 1979 September 20, 1980 June 8, 1981 December 15, 1983 May 1, 1985 March 9, 1988 February 24) and very weak or nearly absent, in 1979 March 21 and December 12, and in 1989 March 2. This behavior is clearly correlated with the presence of shell absorptions.

It is likely that the O I emission originates, at least partially, in the cool M giant which provides a wealth of neutral oxygen which can be excited by fluorescence by the Lyβ photons produced near the hot component. It is also possible that the λ1300 emission has a component due to the Si III $^3P^N\,^3P^o$ transition. The lower term ($^3P^o$) of this transition is metastable and strongly populated (it gives origin to the Si III] λ1892 line). Collisional excitation from $^3P^o$ can populate the ^3P term, and in the decay Si III λ1300 photons are produced.

There are indications, in some spectra, of a possible P Cygni profile in the N V line, although we can not exclude that this effect is only apparent and due to the Lyman-α absorption

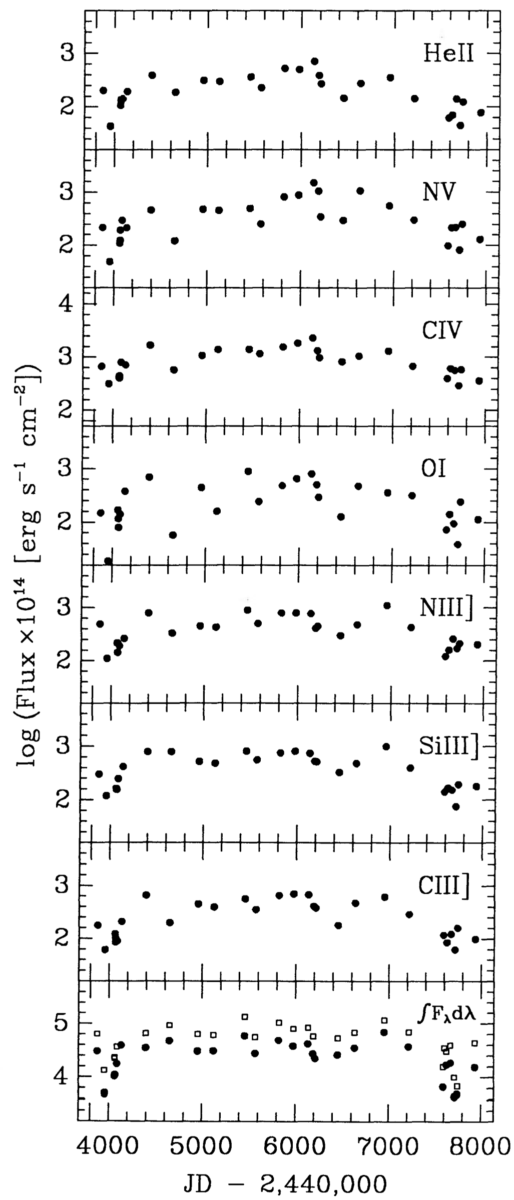

FIG. 5.—Time variability of the emission-line fluxes of T CrB and of the integrated flux. In the bottom panel, dots refer to the integrated flux in the SWP only, open squares to the total SWP + LWP flux. All fluxes are reddening corrected. Note the deep minima in 1979 March and 1989 July (see the corresponding spectra in Fig. 1) and the plateau between 1981 and 1988.

TABLE 3

REDDENING-CORRECTED FLUXES OF STRONGEST EMISSION LINES

SWP Number	F_{SW}	N V λ1240	O I λ1300	N IV λ1487	C IV λ1550	He II λ1640	O III] λ1663	N III] λ1750	Si III] λ1892	C III] λ1909	log N_e
3815	3.03	218	150	138	670	202	84	494	302	175	11.21
4750	0.51	49	19	115	314	44	38	111	119	62	10.71
5759	1.05	110	170	96:	430	108	76	216	162	121	10.45
5803	1.11	125:	80	80	407	137	104	213	162	102	10.58
5804	1.08	194	117	80	442	132	98	144	157	85	10.69
6062	1.76	298	141	173	795	143	90	192	249	89	9.75
6593	3.88	215	380	389	712	196	247	264	414	207	10.74
9228	3.53	469	694	311	1681	395	350	796	795	663	10.37
13330	4.77	123::	58:	209	575	190	193	330	795	200	10.20
15762	3.07	481	448	217	1077	318	196	454	518	457	10.32
17104	3.10	455	160	226	1399	301	234	427	480	398	10.37
19869	5.93	498	891	272	1409	366	406	900	811	572	10.49
20744	2.80	253	241	153	1166	228	235	502	558	360	10.56
22867	4.89	825	482	171	1563	533	407	804	755	665	10.33
24104	3.82	880	648	206	1857	506	316	793	813	711	10.33
25401	4.18	1516	799	359	2345	718	396	776	734	685	10.28
25834	2.73	1050	503	177	1344	392	226	413	524	418	10.40
25999	2.26	353	297	246	991	273	253	452	512	385	10.44
27556	2.59	300:	128	93	831	146	129	297	323	181	10.66
28716	3.53	1070	475	144	1069	278	175	480	479	481	10.23
31095	6.92	562:	358	332	1314	359	438	1120	992	628	10.57
32973	3.72	306:	316	199	680	145	177	428	398	293	10.46
35648	0.68	99	73	83	398	62	83	123	143	120	10.36
35959	1.72	216	143	112	611	71	147	159	168	86	10.72
36313	1.84	221	95	85:	573	142	109	259	154	123	10.40
36611	0.45	82	39	53	297	45	48	173	75	63	10.36
36774	0.50	252	244	152	586	126	112	212	195	160	10.38
38170	1.54	132:	114	70	365	79	71	205	180	100	10.67

NOTES.—Units are: 10^{-10} ergs cm^{-2} s^{-1} for the integrated flux over the SWP wavelength region (F_{SW}) and 10^{-14} ergs cm^{-2} s^{-1} for the line fluxes. All fluxes are reddening corrected for $E_{B-V} = 0.15$.

being either variable in width or not filled in, at these epochs, by the geocoronal Lyman-α emission (see also next section). If true, the P Cygni profile would indicate an outflow velocity larger than 2000 km s^{-1}, in analogy to the case of AG Dra (Viotti et al. 1983).

High-resolution spectra indicate that the Si III] λ1892 and C III] λ1909 emissions have narrow cores and rather broad wings (Fig. 6). The width of the broad component (336 km s^{-1}) is comparable to that derived by Kraft (1958) for the Hα and Hβ lines (∼330 km s^{-1}), while the narrow component is only instrumentally broadened. Similar profiles are seen in the N III] λ1750 lines in spite of the low S/N ratio (Fig. 6).

The high-resolution spectra, although partially underexposed, clearly indicate that the high-excitation permitted lines (C IV λ1550 Å, He II λ1640 Å) show instead only a very shallow and broad profile with half-width at zero intensity HWZI ≥ 1300 km s^{-1} (see Fig. 7, and the discussion in § 5.1).

3.4. *The Absorption Lines*

As mentioned in § 3.2, the continuum of T CrB is generally "eroded" by a shell-like absorption spectrum. A typical shell spectrum is shown in Figure 4 (*bottom*). The "shell" features have been generally present, with variations, during the whole period covered by the *IUE* observations and have reached a maximum in 1981 February. Then the continuum gradually became steeper at short wavelengths and the absorptions weakened. By 1985 March, the spectrum was an almost pure emission-line spectrum, with no detectable trace of the shell. However, as early as June of the same year, and more clearly in 1986 January, the shell appeared again. It is still present in the last spectrum obtained in 1990.

It is worth recalling that the detection, during quiescence, of an optically thick A-type shell was reported in photographic spectra at wavelengths shorter than 4100 Å as early as in 1943 by Minkowski (1943) and Swings & Struve (1943).

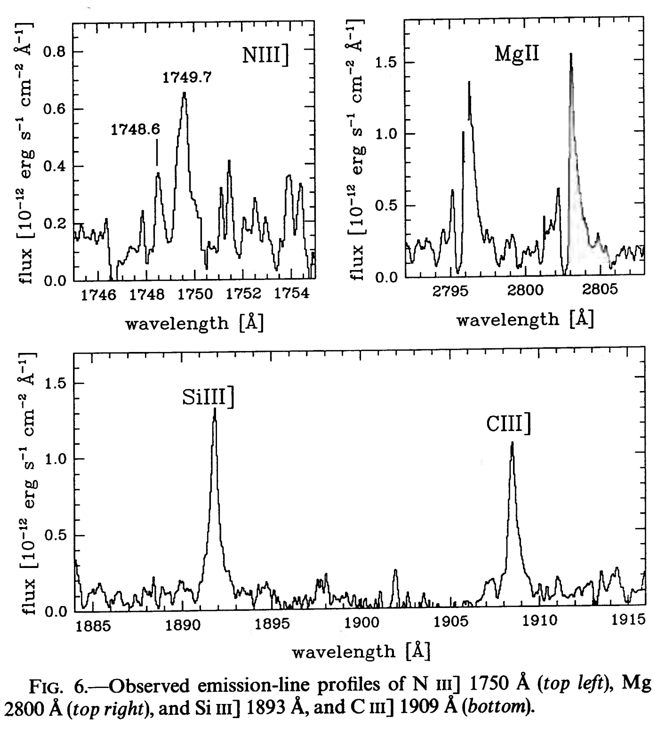

FIG. 6.—Observed emission-line profiles of N III] 1750 Å (*top left*), Mg II 2800 Å (*top right*), and Si III] 1893 Å, and C III] 1909 Å (*bottom*).

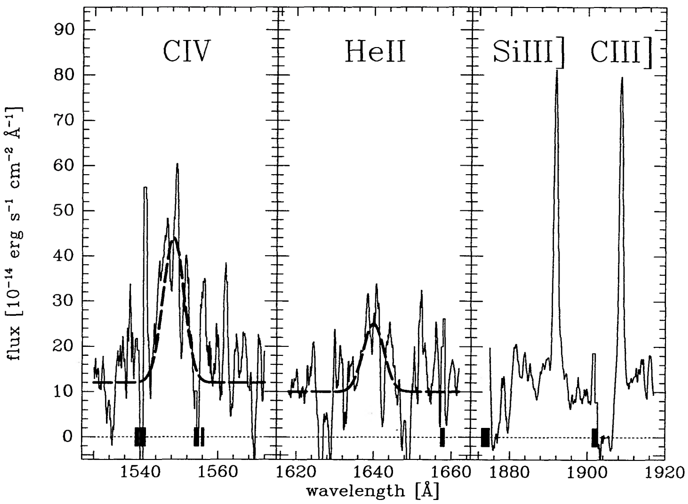

FIG. 7.—Comparison between the line widths of high ionization lines and intercombination lines. The data are the average of three separate observations. Both C IV and He II are substantially broader lines than Si III] and C III]. The dashed Gaussians are conservative fits to the data, indicating a HWZI ≥ 1300 km s^{-1}. The wavelength interval is the same in all panels (so that, in velocity space, the lines in the right panel would appear about 20% narrower). The black bars on the zero line indicate regions of exceedingly high noise and were excluded from the plot. With the exclusion of the line around λ1532, regions with no signal correspond to order edges.

Although the orbital sampling of our observations is not very high, and cycle-to-cycle variations are likely, there are indications that a weakening of the shell features occurs around phase 0 (giant star behind), while the shell is generally strong around phase 0.4 (but, on one occasion [20 September 1979, SWP 6593]), also at phase 0.14).

Not surprisingly, when the shell is present, a strong and wide Lyα absorption feature is also clearly evident.

The assignment of correct identifications to the shell features is difficult in low-resolution *IUE* spectra. We have been helped in this task by the similarity, at some epochs, between the far-UV absorption spectrum of T CrB and that of the symbiotic star CH Cyg (Hack & Selvelli 1982; Mikolajevska, Selvelli, & Hack 1988) during outburst phases since for this latter object high- and low-resolution spectra were available at the same time. The overall absorption spectrum of T CrB (and CH Cyg) is, at some epochs, very similar to that of late-B and early-A supergiants with lines mainly of once ionized metals (Fe II, Ni II, Cr II). This seems to be a typical signature of symbiotic stars during activity phases and mimics an optically thick, $T \sim 10^4$ K shell surrounding the hot component (Sahade & Wood 1978). Kenyon (1986) has also reported recently a similar behavior for the symbiotic star PU Vul.

Table 2 lists also the most important absorption features seen at low resolution and the proposed identifications. The majority of lines are identified with Fe II and Ni II. A high-resolution LWP spectrum obtained on 1982 April 30 has confirmed the presence of many absorption lines from once ionized metals, mainly Fe II and Cr II. All strong transitions (multiplets) are represented, including those arising from levels with excitation potentials as high as ~8 eV for Fe II and 4.5 eV for Cr II. This is a clear indication that the density in the region where these absorption originate is rather high. The Fe II lines of multiplets UV 1 and 2 show two stellar components separated by ~0.2 Å, while the other multiplets have only one component. Figure 8 shows a region of the spectrum around 2750 Å where Fe II and Cr II absorptions are prominent.

4. RESULTS

4.1. *The UV Luminosity and the Mass Accretion Rate*

The total UV flux of T CrB did not change significantly from 1979 January to 1990 January with the exception of two short periods of deep minima around 1979 March and 1989 July. From the average UV flux (7.9 ± 2.4 10^{-10} ergs cm^{-2} s^{-1}) and assuming a distance to T CrB of 1300 pc (Patterson 1984), the average value of the integrated luminosity is (1.5 ± 0.4) × 10^{35} ergs s^{-1} (~40 ± 10 $L_\odot$). A peak luminosity of 70 $L_\odot$ has been reached in 1983 May.

In a recent UV study of a sample of about 10 old novae, Cassatella et al. (1990) have found typical UV luminosities in the range ~1 to ~10 $L_\odot$, the higher value being associated with systems of lower inclination. The inclination of T CrB is rather high ($i \sim 60°$; Kraft 1958; see also § 6), indicating that its observed UV luminosity is much higher than in quiescent novae of the same inclination, and in any case at least as high as the brightest members of the class (Krautter et al. 1981).

Accretion onto a compact object is a commonly accepted mechanism for producing the observed UV luminosity in cataclysmic variables. In most cases the mass transfer is achieved through Roche-lobe overflow but wind accretion can also be effective, especially for systems containing a mass-losing primary. In absence of (strong) magnetic fields, matter accretes onto the compact object forming an accretion disk. $\dot{M}$ can be estimated if the disk luminosity and the nature of the accreting object are known or assumed. In this case, $\dot{M} = 2R_2 L/GM_2$, where R_2 and M_2 are the radius and mass of accreting object, respectively. The mass accretion rate thus obtained is not model dependent but requires the knowledge of the bolometric accretion luminosity. In general, the mass accretion rate is underestimated if only a limited spectral range is available (Verbunt & Wade 1984). However, if most of the disk luminosity is emitted in the UV, as it seems to be the case for T CrB, then L_{UV} is not much smaller than L_{disk} and can be used to provide a first estimate of L_{disk} and, therefore, to set a (lower) limit to $\dot{M}$.

In what follows we assume that the accreting object is a white dwarf. This assumption is justified by three direct UV observational evidences (which are reported below), and several other indications (reported in § 5) which are hardly compatible with the presence of a main-sequence companion:

1. The disk luminosity is radiated mostly in the ultraviolet,

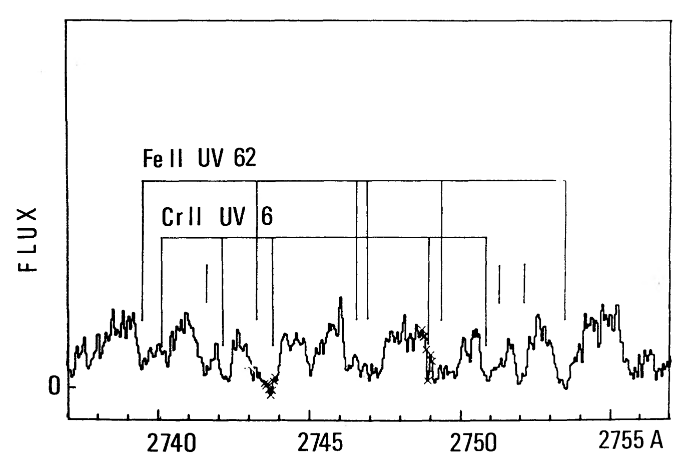

FIG. 8.—Portion of a high-resolution spectrum of T CrB obtained on 1981 March 28 (LWP 1536) showing several absorption lines from Fe II and Cr II. Fluxes are in arbitrary units.

with a negligible contribution to the optical. This is a strong indication in favor of a white dwarf accretor. Indeed, an accretion luminosity of about 40 $L_\odot$ can be produced also by, say, a 2 $M_\odot$, 2 $R_\odot$, main-sequence star accreting at the exceptionally high rate of $\dot{M} \sim 16 \times 10^{20}$ g s^{-1}. However, the spectral distribution of such a disk would be very different from that of a white dwarf accretor (Bath 1977, 1980; Bath & Pringle 1982). Since the accretion disk temperature varies as $(\dot{M}/R^3)^{1/4}$, in order to have with a main-sequence accretor the same spectral distribution as that produced by accretion onto a white dwarf the accretion rate must be increased by a factor 10^6. But in this case an extremely high disk luminosity is produced. In other words, a main-sequence accretor is expected to emit mostly in the optical region, in contrast with the observed behavior of T CrB whose disk luminosity is emitted almost entirely below 3200 Å.

2. The high-excitation He II λ1640 emission line is indicative of temperatures higher than 10^5 K (Ferland et al. 1982). It is very difficult to reconcile this value with accretion onto a main-sequence star, and this suggests in itself the presence of a compact accretor. Note that in interactive binaries, the presence of He II emission is a strong discriminator between the systems with white dwarfs and those with main-sequence accretors: in the semidetached systems of Algol and W Ser type, that have an early main-sequence star as the compact component, while high excitation lines of C IV, N V, and Si IV are generally present the He II λ1640 emission is always missing (see Plavec et al. 1984 and McCluskey & Sahade 1987).

3. The profiles of the C IV λ1550 and He II λ1640 emission lines in high-resolution spectra are very wide and shallow, and set a lower limit of ∼1300 km s^{-1} for the HWZI. These high velocities are not typical of phenomena taking place around a low-mass main-sequence accretor (see also § 5.1). Highly turbulent disks could conceivably produce velocities higher than v_{esc} from a main-sequence star (although not by this much), but there is no way they could account for the He II emission.

With the assumption of a white dwarf accretor and taking for a first rough estimate indicative values of $L_{disk} = 40\ L_\odot$, $M_2 = 1\ M_\odot$ and $R_2 = 0.01\ R_\odot$, the average accretion rate is $2.5 \times 10^{-8}\ M_\odot$ yr^{-1} = 1.6×10^{18} g s^{-1} (see § 6 for further discussion).

4.2. *Remarks on the Slope of the UV Continuum*

The average value of the spectral index ($\alpha \sim 1.26$) in T CrB is lower than that generally observed in CVs. The brightest members of quiescent novae have $\alpha \sim 2.0$, dwarf novae in outburst also show $\alpha \sim 2.0$, while dwarf novae in quiescence have $\alpha < 1.5$ (Hassall 1985; Szkody 1985). The peculiarity of T CrB is that its low alpha value, similar to that of quiescent dwarf novae, corresponds to a much higher UV luminosity (40 $L_\odot$ vs. ∼1 $L_\odot$).

This low value could be ascribed to an "inclination effect." Warner (1987) has reported a positive correlation in quiescent novae between M_v and cos *i*. Cassatella et al. (1990) have found a similar correlation between the UV spectral index α and cos *i* in quiescent old novae. Systems seen pole-on tend to have $\alpha > 2.0$, while systems seen edge-on tend to have $\alpha \sim 1.0$. In this correlation, a value of $\alpha \sim 1.3$ is associated with a system inclination of ∼60°, the most likely value of T CrB.

A low disk temperature is indicated by a comparison with the grids of accretion disk models published by Wade (1984). These models give the expected flux ratios at three wavelengths (S = 1362 Å, M = 2137 Å, and L = 2612 Å) as a function of T_* and T_{min} of the disk, where $T_* = 2T_{max}$. Using our derived average slope we obtain for the ratios S/L and M/L the values 2.3 and 1.3, respectively. These values correspond to temperatures (in 10^3 K) which are intermediate between ($T_* = 24$, $T_{min} = 6$) and ($T_* = 36$, $T_{min} = 6$). Wade's models with such low temperatures give, however, a total disk luminosity in the UV which is lower than that in the optical, in contrast to what is observed. Only models with the highest temperatures ($T_* \sim 10^5$ K) give an optical disk luminosity of less than 0.1 L_{UV}, which seems appropriate for T CrB.

In Wade's grids, the estimated temperatures depend critically on which model is used for the continuum distribution of the disk (whether sum of blackbodies or sum of model atmospheres). In T CrB the Roche lobe radius is larger by a factor of about 100 than in the commonly studied CVs, and as a consequence of this fact its disk structure can be significantly different.

We have also compared the continuum distribution of T CrB at the various epochs with the synthetic models of Kenyon & Webbink (1984) in an attempt to define the nature of the hot component by using the UV diagnostics based on the color indices defined by these authors. The T CrB points (C1 = −0.15, C2 = −0.1) fall (in their Fig. 13) very close to the curve corresponding to a hot stellar source and not to disk accretion onto a MS or WD star (Szuszkiewicz 1985). This indication is in contrast with the observed UV variability and slope of the continuum, which would rather indicate a nonstationary accretion disk. A possible explanation for the discrepancy is indicated by Kenyon & Webbink themselves, who point out that at moderate $\dot{M}$ (∼$3 \times 10^{-8}\ M_\odot$ yr^{-1}), the models of UV continuum for an accreting WD resemble blackbody models of hot stars, especially if the system suffers from interstellar reddening.

As it was already pointed out, the disk luminosity contributes mostly to the satellite UV. On the other hand, if the observed far-UV continuum slope is extrapolated toward the visible, an extra contribution by the disk (several solar luminosities) to the optical luminosity of the red giant (about 100 $L_\odot$) is expected and should be detectable by the FES photometry. Given the absence of such contribution, the above power-law approximation breaks down around 3000 Å, probably because the disk becomes optically thin in its cooler outermost layers. This enables us to set a rough limit to the dimension of the optically thick region R_{th} of the disk (responsible for the UV emission): on the assumption that the most external emitting layer radiates like a blackbody at around 10^4 K and that $R_{th} \gg R_*$ (R_* being the inner disk radius $\sim R_{WD} \sim 0.01\ R_\odot$), one obtains from standard formulae

$$R_{th} = (10^4/T_*)^{-4/3} R_* \approx 0.5\ R_\odot ,$$

where $T_* = (3GM\dot{M}/8\pi R_*^3 \sigma)^{1/4} \lesssim 2 \times 10^5$ K is the inner disk temperature. Combining this value with that of the disk luminosity, we obtain an estimate of the average disk temperature of ∼20,000 K.

4.3. *The Hydrogen Recombination Continuum*

The hydrogen free-free (ff) and free-bound (fb) emission is generally an important component of the observed UV energy distribution in objects like symbiotic stars, to which T CrB can be associated. As decribed in § 3.2, the hydrogen free-free plus bound-free emission could affect the slope of the continuum (causing it to appear flatter) and therefore the estimate of the accretion disk luminosity. A determination of this contribution is not in general possible for the lack of simultaneous optical and UV observations. However, an estimate of the contribution by these processes can be made by using the Hβ flux in the assumption that the emitting volume is the same for the ff + bf emission and for the Hβ line.

In this case one can easily estimate the flux $F_{\rm ff+fb}(\lambda)$ contributed by gas emission from the observed flux in Hβ:

$$F_{\rm ff+fb}(\lambda) = \frac{\Gamma_\lambda}{4.1\ 10^{-22} T_e^{-0.88}} F({\rm H}\beta)\ ,$$

where Γ_λ is the ff + fb emission coefficient, and T_e is the electron temperature. Taking $T_e = 10{,}000$ K (§ 4.6), $\lambda = 2800$ Å, $F({\rm H}\beta) = 2 \times 10^{-12}$ ergs cm^{-2} s^{-1} (Blair et al. 1983; Kenyon & Garcia 1986; Cassatella et al. 1992) one obtains $F_{\rm ff+fb}$(2800 Å) = 4.4×10^{-15} ergs cm^{-2} s^{-1} A^{-1}, which represents a small contribution (less than 10%) to the observed flux in the *IUE* long-wavelength range and should not affect significantly the slope of the continuum. This is confirmed by the combined optical-ultraviolet spectrum shown in Figure 2. The recombination continuum is probably variable, but in any case its contribution to the UV luminosity and the slope of the continuum can be neglected, at least in first approximation.

4.4. *Wind Accretion*

It is well known (see, e.g., Reimers 1981) that red giants have quite large wind mass-loss rates ($\dot{M}_w \sim 10^{-7}$ to 10^{-8} $M_\odot$ yr^{-1}) and low wind velocities. In T CrB this situation might favor the capture by the companion of a consistent fraction of the outflowing material. Wind accretion occurs within a cylindrical region with axis along the relative wind direction and radius:

$$r_{\rm acc} \sim \frac{2GM_2}{v_{\rm rel}^2 + c_s^2}$$

(Bondi & Hoyle 1944; see also Livio & Warner 1984 and Livio 1986) where $v_{\rm rel}^2 = v_{\rm orb}^2 + v_{\rm wind}^2$ and c_s is the sound speed. The accretion rate can be estimated from the relation $\dot{M}_{\rm accr} = \epsilon \dot{M}_{\rm wind}$, where $\epsilon = \pi r_{\rm accr}^2/(4\pi a^2) = G^2 M_2^2/(a^2 v_{\rm rel}^4)$ is the fraction of the wind which is accreted and a is the semiaxis of the orbit (Jura & Helfand 1984). For the parameters appropriate for T CrB, assuming a white dwarf accretor of 1 $M_\odot$, $v_{\rm orb} \sim 45$ km s^{-1}, $v_{\rm wind} \sim 20$ km s^{-1}, and $a \sim 100\ R_\odot$, we obtain a value for ϵ close to 0.5. A substantial fraction of the giant wind is therefore accreted by the companion. In absence of direct observations, assuming $\dot{M}_{\rm wind} \sim 10^{-8}$ $M_\odot$ yr^{-1}, it follows that $\dot{M}_{\rm acc} \sim 5 \times 10^{-9}$ $M_\odot$ yr^{-1} and $L_{\rm acc} \sim 3 \times 10^{34}$ ergs s^{-1}. Wind-accretion luminosity is therefore likely to represent a nonnegligible part of the total luminosity. Note that this conclusion is strictly related to the assumption that the companion is a white dwarf.

4.5. *The Electron Density*

A diagnostic commonly employed in symbiotics and related objects for the determination of the electron density is based on the intensity ratio of the Si III] λ1892 to C III] λ1909 intercombination lines (Nussbaumer & Stencel 1989; Feibelman & Aller 1987). This method is quite insensitive to the electron temperature.

Consistent with the similar excitation levels of the two lines, both strong in the spectrum of T CrB, we assume that they are formed in the same emitting region(s). High-resolution data suggest the presence of two components which however have similar relative intensities in both lines. In addition, we assume that (1) the ionization fraction [N(Si III)/N(Si I)]/[N(C III)/N(C I)] is 0.496 (Jordan 1969); (2) the Si and C abundances are solar; (3) the electron temperature of the emitting region is $\sim$10,000 K. The electron densities are reported in the last column of Table 3.

The mean value of the electron density since 1979 January is 2.8×10^{10} cm^{-3}. The highest density (1.2×10^{11} cm^{-3}) corresponds to the peculiar spectrum of 1981 February, while the lowest value (1.8×10^{10} cm^{-3}) was recorded on 1985 March 9.

As an independent estimate of the electron density we have used the N III] multiplet around 1750 Å, whose line components were detected in the high resolution SWP spectra (see Fig. 6). From the measured ratios of the 1748.6 Å, 1749.7 Å, and 1754.0 Å lines and the calculations by Altamore et al. (1981), we have obtained $N_e = 1.7 \times 10^{10}$ cm^{-3} on 1980 June, and $N_e = 1.3 \times 10^{10}$ cm^{-3} on 1981 February, in agreement with the electron density reported in Table 3. In what follows, we will therefore assume an electron density equal to the mean value reported above of $N_e = 2.8 \times 10^{10}$ cm^{-3}.

4.6. *The Zanstra Temperature*

The He II λ1640 emission, as a recombination line of an ion requiring 54.4 eV for ionization, is an unambiguous indicator of the presence of high-energy radiation in the spectrum. Because of the high energy of its lower level, it is unlikely that the He II λ1640 line is formed by a mechanism other than recombination after radiative ionization. This seems indeed to be the case of T CrB, as indicated by the positive correlation between the He II λ1640 intensity and the UV continuum fluxes (Fig. 5).

Whatever the nature of the ionizing source, it is possible to estimate its temperature using the Zanstra method under the assumption that the ionizing source radiates as a blackbody source shortward of 228 Å (ionization limit of He II). We further assume that the reddening correcting flux of T CrB at 1300 Å, F_{1300}, is entirely contributed by the blackbody source. The flux ratio I_{1640}/F_{1300} provides then a direct indication of the Zanstra temperature (see, e.g., Pottasch 1984). The measured ratios I_{1640}/F_{1300} yield an average temperature $T_Z = 65{,}800 \pm 2500$ K. Because of the assumptions implicit in the definition of the Zanstra temperature, the above value is actually a lower limit to the temperature of the ionizing source.

4.7. *The EUV/Soft X-Ray and the "Hard" X-Ray Luminosity of T Coronae Borealis*

Theory predicts that about one-half of the total gravitational energy released by the gas accreting onto a compact object through a disk should come from the boundary layer. The other half is emitted by the disk. Both theory (Pringle 1977; Pringle & Savonie 1979; Tylenda 1981) and observations (Patterson & Raymond 1985a, b) state that at low accretion rates ($< 10^{16}$ g s^{-1}), the gas in the boundary layer is optically thin and must be heated to very high temperatures ($\sim 10^8$ K) in order to radiate away its energy, mostly in the hard X-ray portion of the spectrum. Instead at high accretion rates ($\gg 10^{16}$ g s^{-1}) the boundary layer region becomes optically thick and radiates most of its luminosity ($L_{\rm BL}$) at temperatures between 10^5 and 5×10^5 K, thus emitting in the EUV/soft X-ray region of the spectrum. In this case only a very small fraction of the luminosity (less than 1%) is radiated as hard X-rays (Patterson & Raymond 1985a, b).

From the UV luminosity of T CrB, we have obtained an average $\dot{M} \sim 1.6 \times 10^{18}$ g s^{-1}. At these rates T CrB is therefore expected to radiate in the optically thick regime. To our knowledge, there have been no attempts to obtain direct soft X-ray observations of T CrB, and probably the hydrogen column density in the line of sight ($\sim 10^{21}$ cm^{-2}) would have prevented a positive detection. However, an estimate of the number of photons with energies higher than 54.4 eV (i.e., of the EUV/soft X-ray flux) can be obtained from the He II λ1640 emission intensity, whose average value (3.5×10^{-12} ergs s^{-1} cm^{-2}) implies a luminosity of $\sim 7 \times 10^{32}$ ergs s^{-1}. Assuming case B recombination and spherically symmetric geometry we can estimate the number Q_4 of photons with energies higher than $h\nu = 54.4$ eV:

$$Q_4 = \int_{4\nu_0}^{\infty} \frac{L_\nu \, d\nu}{h\nu} = \frac{\alpha^B_{\rm tot}({\rm He}^{++})}{\alpha^{\rm eff}_{1640}} \frac{L_{1640}}{h\nu_{1640}} .$$

Since $\alpha^B_{\rm tot}/\alpha^{\rm eff}_{1640} \sim 3$, and $h\nu_{1640} = 7.5$ eV, we obtain $Q_4 \sim 1.7 \times 10^{44}$ photons. If we assign an average typical energy of 75 eV to those photons, the luminosity below λ228 is about 2×10^{34} ergs s^{-1}. This is, however, a lower limit for $L_{\rm EUV}$: not only is it unlikely that *all* photons ionize He II, but also that we are in a spherically symmetric situation. The fraction ξ of the boundary layer EUV radiation which illuminates and ionizes the upper layers of the disk and produces He II recombination lines is quite uncertain and depends critically on the geometry of the boundary layer region. If we adopt $\xi \sim 0.1$ (Patterson & Raymond 1985b), we obtain $L_{\rm EUV} \sim 2 \times 10^{35}$ ergs s^{-1}. From this value we can estimate the temperature of the boundary layer using the relation

$$T_{\rm eff} = f^{-1/4}\left(\frac{L_{\rm B.L.}}{4\pi\sigma R^2}\right)^{1/4} ,$$

where $f \sim 10^2$ to $10^{-2.5}$ (Pringle 1977) is the fraction of the white dwarf surface which is covered by the boundary layer. If we take $L_{\rm BL} \sim L_{\rm EUV} \sim 10^{35}$ ergs s^{-1}, $R_2 \sim 10^{-2}$ $R_\odot$, and $f \sim 10^{-2}$, we obtain $T_{\rm B.L.} \sim 4.1 \times 10^5$ K.

Patterson & Raymond (1985b) associate a similar temperature to $L_{1640} \sim 1.0 \times 10^{33}$ and $L_{\rm B.L.} \sim 1.3 \times 10^{36}$ ergs s^{-1}.

T CrB has been positively detected with the *Einstein* IPC "hard" X-ray detector (0.2–4 keV) with a luminosity L_X of about 5×10^{31} ergs s^{-1}. The hard X-ray luminosity of T CrB is very close to the average value (6×10^{31} ergs s^{-1}) found for the few X-ray–detected classical novae (Córdova et al. 1981) and larger than the average value of dwarf novae. This value is much lower than the observed UV and estimated EUV luminosities in T CrB.

If we assume that $L_{\rm UV}$ is produced in the accretion disk while $L_{\rm EUV}$ and L_X are produced near the boundary layer, these results indicate that $L_{\rm UV} \sim L_{\rm EUV} \gg L_X$. This picture is fully consistent with the theoretical predictions for the high accretion rates found in T CrB.

It goes without saying that the hard X-ray luminosity cannot be reconciled with the presence of a main-sequence accretor.

4.8. *$\dot{M}$ from the* He II *λ1640 Intensity*

An independent check for the value of $\dot{M}$ can be made through the $\dot{M}$ − λ1640 luminosity relation given by Patterson & Raymond (1985b) for white dwarf accretors. For a 1 $M_\odot$ WD and our observed He II luminosity, their Table 2 gives mass accretion rates which are intermediate between 10^{18} and 10^{19} g s^{-1}, in good agreement with the estimate of $\dot{M}$ based on the UV continuum only (see § 4.1).

5. DISCUSSION

5.1. *The Nature of the Companion*

A white dwarf companion has been explicitly or implicitly assumed in our previous considerations. There are in fact several indications drawn from the behavior of T CrB in quiescence which are hardly compatible with the presence of a main-sequence companion while they find a natural and self-consistent interpretation in terms of a white dwarf accretor. We recall them here briefly:

1. The bulk of the disk luminosity is emitted in the UV with a negligible contribution in the optical range. The observed UV luminosity (~ 40 $L_\odot$) is about 10 times larger than the average value found in old novae. Producing this luminosity with a main-sequence accretor would require a very high accretion rate, and the disk would emit mostly in the optical, in contradiction with the observations.

2. Rather strong He II and N V emissions are generally present. These emissions are indicative of temperatures of the order of 10^5 K and, in CVs, are naturally associated with the boundary layer. Only a white dwarf accretor at the calculated $\dot{M}$ can explain at the same time both the observed UV luminosity and the high temperature required to produce the He II λ1640 emission. We note that, "historically," the presence of a strong He II λ4686 line was reported as early as in 1921 by Adams & Joy (1921) and subsequently by many other observers until epochs close to the 1946 outburst (Joy 1938; Hachenberg & Wellmann 1938; Minkowski 1939, 1943; Swings, Elvey, & Struve 1940; Swings & Struve 1941, 1943).

3. The X-ray luminosity is of the same order of that found in the X-ray–brightest old novae, $L_X \sim 5 \times 10^{31}$ ergs s^{-1} (Córdova et al. 1981; Becker 1989) and cannot be explained in terms of accretion onto a main-sequence star. Note that no X-ray emission at this level can be produced by the M giant.

4. The profiles of the C IV λ1550 and He II λ1640 emission lines in high-resolution spectra are very wide and shallow (see Fig. 7 and § 3.3). C IV, the strongest emission line in the low-resolution spectra, is hardly evident at high resolution, while weaker lines (e.g., Si III] λ1892 and C III] λ1909) are much sharper and clearly present (see Figs. 6 and 7). We interpret this result as an indication of strong rotational broadening since C IV and He II originate in the innermost disk/boundary layer region. The observed velocity for C IV (>1300 km s^{-1}) is higher than that expected at the surface of a main-sequence accretor with $M \sim 2$ $M_\odot$. Note that the intrinsic rotational velocity in C IV λ1550 after allowance for the orbital inclination ($i < 68°$) is larger than 1400 km s^{-1}.

5. Although not a direct observational evidence, the fact that the EUV luminosity emitted below 228 Å ($\sim 2 \times 10^{35}$ ergs s^{-1}, estimated from the He II λ1640 emission) is comparable with the observed UV luminosity, while the X-ray luminosity is much lower, also lends support to the white dwarf assumption, since it agrees well with the theoretical predictions for a standard disk around a white dwarf accretor (Patterson & Raymond 1985a, b) at an accretion rate similar to that of T CrB.

6. Rapid flickering in the light curve of T CrB with a time scale of 10–100 s has been reported in several studies (Walker 1957; Bianchini & Middleditch 1976; Walker 1977; Oskanyan 1983; Khozevnikov 1988). The flickering, almost identical to

that commonly observed in dwarf novae and other short period cataclysmic variables, is indicative of phenomena associated with the presence of a white dwarf (Walker 1977).

5.2. *The Radial Velocity Problem*

All the arguments reported in the previous section in favor of a white dwarf are "disturbed" by the results of the orbital data for T CrB which suggest a mass for the companion higher than that acceptable for a white dwarf (Kraft 1958; Paczyński 1965).

The problem of the radial velocity is of critical importance and requires a detailed comment.

Radial velocity variations in the giant's absorption lines were first reported by Sandford (1949) who proposed a period of about 230 days. The subsequent investigation by Kraft (1958) lead to an improved period of 227.6 days and to the detection of radial velocity variations also in the hydrogen emissions whose considerable width (~ 300 km s^{-1}) together with their small velocity range ($K_2 \sim 30$ km s^{-1}) prevented Sandford from detecting the radial velocity changes. Kraft used several plates for the determination of K_1 (~ 23 km s^{-1}), but seven plates only for the determination of K_2. Paczyński, using the same data as Kraft, improved the curves obtaining $K_1 \sim 22.9$, $K_2 \sim 31.3 \pm 2$ km s^{-1}, and $q = M_1/M_2 \sim 1.4 \pm 0.2$. Adopting an inclination $i \sim 68°$, the resulting masses were $M_1 \sim 2.6\ M_\odot$ and $M_2 \sim 1.9\ M_\odot$, thus placing the hot component above the Chandrasekhar limit. A larger value for i is unlikely since there is no evidence of eclipses in the optical. We stress that a value for i close to 90° cannot be completely ruled out on the basis of ground observations alone since an eclipse of the hot component would be very difficult to detect because the hot component contributes very little or nothing at $\lambda \sim 5000$ Å. However, as mentioned in § 3.2, our UV observations near phase 0.5 have not shown any evidence for eclipses.

The fundamental conclusion concerning the mass of the companion has remained unchecked since Kraft's observations. Recently Kenyon & Garcia (1986) have accurately remeasured K_1, confirming substantially the previous determinations. They have not attempted, however, to remeasure the emission line radial velocities and, in their new determination of the orbital parameters they either have assumed $q > 1.2$ or have used indirect methods to give evidence that $q \sim 1.3$.

The following points must be stressed:

1. The hydrogen emission lines of T CrB are quite wide (~ 330 km s^{-1}) and severely distorted by the absorptions of the giant and show a composite structure.
2. An entire period of the emission lines was covered by only seven points (plates), and only two plates were close to quadratures (velocity maxima).
3. About 30 years have elapsed since Kraft's radial velocity determinations. Even nowadays, in spite of the considerable improvements in the measuring techniques, the problem of how to measure K_2 is serious and difficult. For a critical considerations on the determinations of K_2 see, e.g., Wade (1985), Shafter (1985), and Gilliland, Kemper, & Suntzeff (1986).
4. Kraft (1958) himself, after the laborious operations for the reconstruction of the emission profile, stated that "a non negligible degree of error might still exist in the orbit derived from the hydrogen emissions." Recently, Kraft (1989) has explicitly confirmed the possibility of a substantial uncertainty in the K_2 value.
5. It is not clear whether the hydrogen emissions are necessarily associated with the orbital motion of the hot component.

Considering all these circumstances, an error in excess of about 8 km s^{-1} on the K_2 value reported by Kraft (1958) is not unlikely. A reduction of K_2 by this amount would yield $K_2 \sim K_1 \sim 23$ km s^{-1} and a solution $M_1 \sim M_2 \sim 1.4\ M_\odot$ for the masses, thus allowing the accreting object to be a degenerate dwarf close to the Chandrasekhar limit.

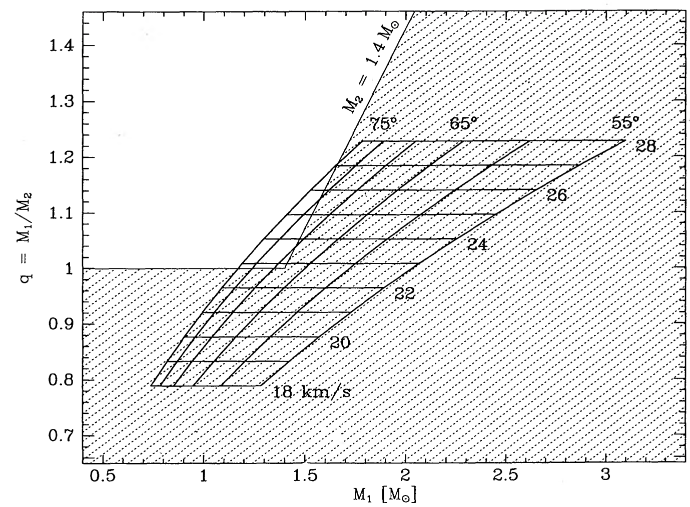

FIG. 9.—The ($q = M_1/M_2$) vs. (M_1) diagram. The grid shows the possible solutions as a function of inclination angle i (horizontal lines) and of K_2 (inclined lines). The shaded area is forbidden by the constraints $q > 1$ and $M_2 < 1.4\ M_\odot$. Only a solution $K_2 \simeq K_1 \sim 23$ km s^{-1}, $M_2 \simeq M_1 \sim 1.4\ M_\odot$ is compatible with the absence of ultraviolet eclipses in the light curve of T CrB.

Note that this is the only solution compatible with $q \geq 1$, $M_2 \leq 1.4\ M_\odot$ and $i \sim 68°$. Figure 9 shows a q versus M_1 diagram for T CrB for the assumption $K_1 = 22.8$ km s^{-1}. The critical lines $q = 1$ and $M_2 = 1.4\ M_\odot$ are also drawn. As one can see, there is little room for variations unless one releases the $q \sim 1$ condition and/or inclination angles higher than 68° are considered, despite the absence of eclipses.

5.3. *The Nature of the 1946 Outburst*

Webbink (1976) and WLTO have interpreted the 1946 outburst in terms of a burst of mass which was transferred from the giant onto the companion. The main reasons for excluding a TNR were both the supposed presence of a main-sequence star and the presence of a secondary maximum, not usually observed in fast novae. Note that in some (slow) classical novae the deep minimum observed after outburst is due to dust which envelops the system, as shown by IR observations, while very fast novae do not usually show the presence of dust.

It is our opinion, however, that the outburst of T CrB can be nevertheless interpreted in terms of a TNR on a white dwarf for at least four reasons:

1. The spectral evolution of T CrB in outburst (Herbig & Neubauer 1946; Sanford 1946; McLaughlin 1946; Bloch et al. 1946) has followed the pattern generally observed in other (very fast) novae. The expansion velocity reached -5000 km s^{-1}, a value of the order of the escape velocity from a massive white dwarf.
2. Photometrically, T CrB has obeyed the same relation M_V^{max}-t_3 followed by the classical (fast) novae (Warner 1987).
3. The maximum luminosity during the outburst was super-Eddington: for the magnitude, distance, the reddening appropriate for T CrB, the absolute visual magnitude was $M_V^{max} \sim -8.0$, implying $L_V^{max} \sim 5 \times 10^{38}$ ergs s^{-1}. These values represent, of course, lower limits for the bolometric quantities (the

Eddington limits for a 1.38 $M_{\odot}$ WD are $M_{bol} = -7.1$ and $L_{bol} = 2.0 \times 10^{38}$ ergs s^{-1}.) A super-Eddington luminosity at maximum is a very strong argument in favor of a TNR model (Truran 1982; Truran & Livio 1988; Starrfield, Sparks, & Shaviv 1988) and can easily explain the extrarapid character of the light curve and the presence of ejection velocities of the order of 5000 km s^{-1}. Also, recent studies (Shore, Sonneborn, & Starrfield 1990) have shown that all the (TNR) recurrent novae have luminosities at maximum light which exceed the Eddington limit.

4. The average value for $\dot{M}$ in quiescence is in perfect agreement with the theoretical expectations (Starrfield et al. 1985; Livio 1988) for a TNR with a recurrence time of $\sim 10^2$ yr on a very massive WD. With this value of $\dot{M}$ (almost constant over 10 years) *there is no need of a burst of matter from the giant to produce the outburst* (and why should the giant eject such bursts of matter at regular intervals?).

Incidentally, we want to mention that some of the argument used by WLTO in favor of an accretion event onto a MS can very well support the presence of a WD in the T CrB system (and therefore a TNR nature of the outburst). We restrict ourselves to two arguments especially related to our UV observations:

1. WLTO state "the UV continuum and emission lines (in quiescence) are rather weak, unlike what is predicted by TNR theories which require high $\dot{M}$ between outbursts. The $\dot{M}$ is too low to refuel a TNR with a recurrence time of 80 years. The He II 1640 emission is rather weak, [unlike what is expected in a WD accretor]." We realize WLTO wrote this statement based on the data available to them. However, we point out that the quiescent UV luminosity is of the order of 40 $L_{\odot}$, much higher than in other novae in quiescence. The He II line is rather strong (average $L_{\lambda 1640} \sim 7 \times 10^{32}$ ergs s^{-1}), and even stronger than what is expected from a WD accretor at the observed $\dot{M}$ (Patterson & Raymond 1985a, b). We recall that a strong He II λ4686 emission was reported at various epochs from 1921 to 1943 (see § 5.1) despite its theoretical intensity being ~ 10 times smaller than that of the λ1640 line. From this fact we can infer that the UV-EUV luminosity was quite high and, therefore, that T CrB has experienced phases of very high mass accretion rate also *before* the 1946 outburst.

2. WLTO add, "The hydrogen emission line profiles extend to only very modest velocities (HWZI = 240 km s^{-1} for Hβ, 370 km s^{-1} for Hα). These velocities are indicative of Keplerian motions near the surface of a main-sequence star." This statement would be correct only if the H lines were formed in the innermost disk region, and lines with higher HWZI were not observed. Instead, in the innermost disk, He II and other high-ionization species (C IV, N V) are dominant. Our *IUE* high-resolution spectra have shown that these species have HWZI > 1300 km s^{-1} (without correction for the inclination).

5.4. *Archeoastronomy: Remarks on the Secondary Maximum in the 1946 Outburst*

A peculiarity of the light curve of T CrB during outbursts is the presence of a secondary maximum about 4 months after the principal one. Webbink (1976) and WLTO have considered the secondary maximum as a strong indication against a TNR event and have interpreted it as the result of the impact of the orbiting material (after circularization) with the surface of the accreting star.

In our opinion, however, this interpretation faces with serious problems when the spectroscopic behavior at the time of the secondary maximum is taken into account (McLaughlin 1947; Sanford 1947, 1949; Herbig & Neubauer 1946). The spectrum was nebular-like until about 100 days after outburst (following the normal spectral evolution of a very fast nova) but then (beginning of 1946 June) the luminosity increased by 1.5 mag, the emission lines (O III, Ne III, He II) became very faint or invisible and a strong shell absorption spectrum appeared which persisted until the end of July when again, at the end of this secondary maximum, strong narrow emissions reappeared. In substance, the secondary maximum was accompanied by a strong increase in the optical continuum and by a decrease in excitation.

This spectral behavior contradicts the outburst model proposed by Webbink (1976) and by WLTO: when the orbiting material strikes the star's surface an increase in excitation, emission-line intensities and continuum temperature is expected, in contrast to what actually observed; note in particular that the He II λ4686 line was very strong *before* the onset of the secondary maximum, then faded to an almost undetectable emission at the epoch of the secondary maximum and was again present as a strong emission at the *end* of the secondary maximum (McLaughlin 1947).

The secondary maximum is associated in time with the appearance of a shell spectrum. The origin and formation of this (stationary) shell can be a subject of speculations that we leave for a future study, but its presence is a well-ascertained *fact* whose relevance has been underestimated. We think that the secondary maximum is physically related to the formation of this optically thick shell.

The emission line spectrum observed before the secondary maximum, and especially the presence of He II recombination lines, indicated the presence of a very hot continuum source. This is in agreement with the results of recent UV observations of novae in outburst which have shown that most of the energy is emitted shortward of λ3200 (Starrfield 1990). Presumably in T CrB a wealth of strong emissions were present also in the unobserved UV (< 3400 Å). The energetic photons of the post-nova were converted by the optically thick, newly formed shell into low-energy photons emitted mostly in the optical, since the shell acted like a pseudophotosphere at rather low temperature (less than 10^4 K). The presence of the optically thick shell surrounding the white dwarf explains also the fading of the emission lines because the shell has prevented the Lyman-continuum photons to reach and excite the surrounding nebula.

In essence, the shell has converted the hot continuum and the emission-line spectrum (emitted mainly in the far UV) into a shell absorption spectrum (emitted mainly in the optical) with the effect of mimicking the occurrence of a secondary maximum. This interpretation is supported by the fact that the high-excitation emission lines reappeared at the end of the secondary maximum. In our opinion, the presence of the secondary maximum is an "artifact" caused only by the lack of bolometric (or at least UV) observations.

We recall that WLTO have instead claimed that in T CrB there was a true bolometric decline before the secondary maximum and that there was no large luminosity hidden in the UV. They have based their arguments on the assumption that at that epoch the spectrum of the M giant appeared completely undisturbed and on the lack of any evidence of the severe heating expected on the M giant hemisphere facing the companion (although the orbital configuration was very unfavorable for the possible detection of this effect). In this respect, we want to stress that it may be hazardous to estimate a bolometric decline from optical observations only; in any case:

1. The optical light curve in 1946 April and May (Pettit 1946a, b, c) clearly indicated the presence of an "extra" component whose optical magnitude was comparable with that of the giant. We interpret this component as the optical tail of the hot radiation emitted by the nova.

2. The line spectrum at the same epoch actually showed strong "disturbances," e.g., several emissions of He I, He II, N III, [Fe II], etc. (McLaughlin 1946; Herbig & Neubauer 1946). The great strength of the He II emissions indicated beyond any doubt the existence of a very strong EUV–UV source whose contribution in the optical range was partially masked by the presence of the giant star.

Note that the situation in T CrB is in contrast with that in classical novae where the companion is generally a red main-sequence star whose (low) luminosity does not affect significantly that of the postnova.

Photometric and spectroscopic observations made in 1946 April and May (Herbig & Neubauer 1946) also reported brightenings in magnitude and "flarings" in various emission lines, a clear indication of activity in the nova, in contrast with the claimed bolometric decline. It is also worth recalling that a third, lower maximum in the light curve ($m_v \sim 9.0$), approximately 4 months after the second one, was marginally claimed by Pettit (1946c) and is present in the light curve reported by Payne-Gaposchkin (1957).

5.5. *The Nova Outburst in a Massive White Dwarf and the Mass of the Shell Ejected by T Coronae Borealis*

During the past years many theoretical and observational studies have taken into account the properties of a TNR in a massive white dwarf in relation to both the interpretation of the RN phenomenon and the identification of a new class of novae (see Shara 1989 for a comprehensive review). Since the mass of the envelope which is necessary to trigger a TNR is a decreasing function of that of the WD, TNR models of recurrent novae require a WD mass close to the Chandrasekhar limit. In this case, the WD can accumulate a critical mass envelope and suffer nova eruptions on much shorter time scale than in other novae. Fast novae also require a rather massive white dwarf in which the envelope mass is quite low. This accounts for their high v_{max} and their very rapid photometric and spectroscopic changes because their pseudophotosphere becomes transparent much sooner ($t_3 \sim$ few days) than in the other novae.

Starrfield et al. (1985) have studied in detail a model of outburst in a 1.38 $M_\odot$ white dwarf accreting matter of solar composition at $\dot{M} = 1.7 \times 10^{-8}$ $M_\odot$ yr^{-1}. The light curve, the interoutburst interval, and the mass of the ejected envelope agreed well with the observations of the recurrent nova U Sco 1979. The subsequent unexpected outburst of U Sco 1987 has forced Starrfield et al. (1988) to produce a new model in order to explain TNRs with such a short interoutburst interval; it is, however, worth stressing that the values of most parameters in their first model are very similar to those of T CrB.

We are convinced that the outburst of T CrB was a TNR on a white dwarf close to the Chandrasekhar limit.

It is not possible to give an exact value for the mass ejected in the 1946 outburst of T CrB, but the very fast spectral evolution during the outburst, and the very rapid decline in brightness, clearly indicate a low mass. We recall that WLTO (1987) have defined some expected observational properties of the TNR recurrent novae in outburst; since the mass of the ejected envelope is smaller ($\sim 10^{-6}$ to 10^{-7} $M_\odot$) than in "normal" novae, WLTO expect that TNR RNs near optical maximum display a spectrum characterized by prominent emission lines and a weak continuum flux whose distribution should remain extremely blue through maximum, rather than cooling to an A or F supergiant spectrum like "normal" novae.

On the basis of these arguments and of the misquoted evidence (see the following) that T CrB showed a *strong* absorption-line spectrum at maximum, WLTO have provided further proofs in favor of an accretion-powered outburst in T CrB.

In our opinion, the above reported considerations of WLTO for the identification of a TNR RN are based on sensible theoretical arguments but not on observational evidence. In fact, the behavior near maximum of the best studied and commonly accepted TNR RNs would hardly fit the expectations of WLTO:

1. In U Sco, the prototype of TNR RN, *IUE* observations have revealed the presence of P Cyg profiles with deep, broad displaced absorption components in spectra taken 5 days after maximum (Williams et al. 1981). These absorption lines have indeed been used to provide an estimate of the mass of the ejected envelope ($\sim 10^{-7}$ $M_\odot$, Williams et al. 1981; $\sim 10^{-8}$ $M_\odot$, Snijders, Sekiguchi, & Cassatella 1990).

2. In T Pyx, during several weeks after the 1966 outburst the hydrogen lines showed P Cyg profiles with violet-shifted sharp and strong absorption components with velocities near -2000 km s^{-1} (Catchpole 1969; Chincarini & Rosino 1969). These velocities are in agreement with those given by Adams & Joy (1920) for the 1920 outburst when three strongly displaced absorption systems were reported. Note also that during the rise to visual maximum in the 1966 outburst the broad-band colors of T Pyx become redder (Eggen, Mathewson, & Serkowsky 1967).

3. A strong UV continuum is reported for V394 CrA 1987, although the first *IUE* observation were secured about 20 days after outburst (Starrfield et al. 1988; Snijders et al. 1990).

4. In Nova LMC 1990 No. 2, the continuum accounts for about 76% of the total UV flux in the SWP range (1200–2000 Å) and all of the flux in the LWP range (2000–3200 Å) (Shore et al. 1990). Nova LMC 1990 No. 2 did not display P Cyg profiles, "in marked contrast to other recurrent novae whose outburst was observed with *IUE*" (Shore et al. 1990).

In any case, we want to stress that spectroscopic observations of T CrB made immediately before and at the time of maximum (1946 February 12) indeed showed the presence of conspicuous emission lines of H, He I, He II, Fe II, and Ca II etc. (McLaughlin 1946; Bloch et al. 1946; Herbig & Neubauer 1946; Sanford 1946, 1949), while most "normal" novae at maximum display an A supergiant-like spectrum and only *after* maximum do the emission lines appear.

We want also to mention that in T CrB at maximum the absorption lines were reported as "hazy" (Herbig & Neubauer 1946) or "very hazy" (McLaughlin 1946) and not as "strong" as mentioned by WLTO (footnote 5, p. 669). Note that the most displaced absorption components (~ -5000 km s^{-1}) lasted a few days only and were absent in spectra taken 3 days after maximum (Herbig & Neubauer 1946). Five days after maximum, only components at ~ -500 km s^{-1} or at smaller v_{exp} were reported. Instead, *IUE* observations of U Sco made 5 days after maximum show the presence of deep absorption components with displacements up to -7500 km s^{-1} (Williams et al. 1981).

We interpret all this as an indication that the mass of the envelope in T CrB was smaller than that of U Sco, or, in any case, quite small, as expected for TNR recurrent novae.

An accurate estimate of the mass of the envelope ejected by T CrB during outburst would be very important. If, as indicated from the above considerations, M_{env} is very low ($\sim 10^{-7}$ $M_\odot$), this would indicate that the observed $\dot{M} \sim 2$–3×10^{-8} $M_\odot$ yr^{-1}, and with a quiescent period of ~ 100 yr, the mass of the WD increases with time as a net result of each cycle of mass acretion during the "quiescent" interoutburst phase and of mass ejection during outburst. If, as suggested by us, the mass of WD in T CrB is near the Chandrasekhar limit, its ultimate fate will be a Type I SN explosion. A similar destiny has been predicted for U Sco and other TNR recurrent novae by Starrfield et al. (1988, 1991), a consequence of the fact that RNs eject a low-mass envelope which represents only a small fraction of the amount of mass accreted before the explosion.

5.6. *Is T Coronae Borealis an* ONeMg *Recurrent Nova?*

Starrfield, Sparks, & Truran (1986) and Truran & Livio (1986) have identified a subclass of novae (about one-third of the total) which are characterized by the ejection, during the outburst, of material enriched in the elements from oxygen to aluminum, and especially in neon. In this subclass of novae, the photometric development is that of the "fast" or "very fast" class, the velocities of the ejecta are much higher than in novae with CO white dwarfs, and the mass of the expelled envelope is smaller.

Since the enriched material is not produced during the outburst, it must originate from the core of an ONeMg white dwarf (Ferland & Shields 1978) after mixing with the accreted gas through a mechanism (diffusion?; shear mixing during the accretion process?) which, so far, is not clearly understood (see Shara 1989). Evolutionary considerations have shown that only massive WDs can have a ONeMg core. Hydrodynamic simulations of ONeMg novae have been produced by Starrfield et al. (1986) who have studied TNR after fast accretion ($\dot{M} \sim 10^{18}$ g s^{-1}) on the surface of a 1.25 $M_\odot$ WD. These simulations have produced a model of nova characterized by an extremely violent TNR with ejection velocities of the order of several thousand km s^{-1}, by a low mass of the ejected envelope, and by super-Eddington luminosity at maximum.

Starrfield et al. (1991) have pointed out that the ejecta of RNs do not show evidence for high concentration of heavy nuclei and Ne, although the massive WD in these systems is likely to be a ONeMg WD. They have interpreted this as an evidence that in these systems there has been no mixing between the material of the WD interior and that accumulated in its outer part.

We point out, however, that Ne was a strong component of the emission line spectrum of T CrB at several epochs. Pre-outburst spectroscopic observations made from 1938 to 1943 by Joy (1938), Minkowski (1939), Swings et al. (1940), and Swings & Struve (1941, 1943) have always reported the presence of [Ne III] lines, sometimes even of both [Ne III] and [Ne V]. Immediately after outburst, Sanford (1949) reported the simultaneous presence of [Ne III] and [Ne V] as prominent lines from 1946 to 1947 (except during the secondary maximum, when no emission lines were present at all). Kraft (1958) described the [Ne III] emission lines as "fairly strong," while the other common nebular lines (e.g., [O III] $\lambda\lambda$4958, 5007), which are usually quite stronger, were described as very faint, or not detectable.

An overabundance of Ne in T CrB is clearly indicated by these "archive" data. However, the fact that strong Ne lines were observed also *before* and 10 years after the outburst is not of easy interpretation and suggests that any consideration based on the abundances argument must be treated with some caution.

We suggest tentatively that the giant was retransferring to the WD that part of the material ejected in the previous outburst that was intercepted by its outer layers although we are aware that this hypothesis encounters serious difficulties owing to the geometry of the system: less than one-tenth of the mass of the ejected envelope is directly intercepted by the giant.

If the overabundance of neon in T CrB originates from the white dwarf core, this would imply that core material has been mixed with the outer layers by shear mixing during the accretion process (Livio & Truran 1987). The other possible mechanism, i.e., diffusion, cannot work in RNs because for a significative mixing it requires time intervals much longer than the recurrence period. The fact that T CrB is apparently the only recurrent nova to exhibit enrichment of neon can be tentatively ascribed to the fact that shear mixing has been less effective in the other recurrent novae because of their shorter time interval between outbursts.

An overabundance of helium is evident from our *IUE* spectra of T CrB. The observed ratio He II λ1640/H$\beta \sim 3$, sets a lower limit He/H ~ 1 on the assumption that all helium is in the form of He II, but the presence of the He I emission at 3188 Å and that of several lines of the Paschen series of He II, which are generally absent in similar objects, indicates an even higher ratio. Note that enhanced He/H ratios are common in nova ejecta and are interpreted as a consequence of shear mixing with a helium-rich layer left behind on the white dwarf surface from the previous outburst. We think that the same mechanism proposed for neon can be also invoked to explain the overabundance of helium in T CrB.

We recall that Williams & Ferguson (1982) and Williams (1990) have reported that the material transferred from the secondary in CVs and RNs shows evidence of helium enrichments, while Snijders (1986) in a study of the recurrent nova RS Oph has found enrichment of nitrogen in the material transferred from the giant.

6. A MODEL FOR T CORONAE BOREALIS IN QUIESCENCE: THE ORIGIN OF THE CONTINUUM AND LINE SPECTRUM

UV and other observations of T CrB have provided a large amount of data which "constrain" the choice of a physical model. As pointed out in the previous sections, the observations have led to a consistent interpretation in terms of a high and variable mass transfer from the giant onto a massive white dwarf. Assuming $M_1 \sim M_2 \sim 1.4$ $M_\odot$, the relation $R_{equiv}^{Lobe} = 1.353 \times 10^{11} P^{2/3} (M_1/M_\odot)^{1/3}$ cm yields $R_{equiv} \sim 80$ $R_\odot$, a radius which is typical for an M3 giant. The system is semidetached and mass transfer occurs primarily via Roche lobe overflow, although wind accretion might be nonnegligible (see § 4.4). The changes observed in the UV continuum can be ascribed mainly to the variable mass accretion rate. The white dwarf lobe has a radius which is comparable to that of the giant and is partially filled by the gas streaming from L_1 and by the gas transported by the wind.

The observed UV luminosity $L_{UV} \sim 40$ $L_\odot$ is a lower limit to the "intrinsic" (face-on and bolometric) disk luminosity L_{disk}. A rather high inclination of the system is indicated by the observed rotational broadening of the C IV and He II emission lines, but values larger than 68° are precluded by the absence of UV eclipses. If we take $i \sim 60°$ and assume that the relation M_v versus inclination (Paczyński & Schwarzenberg-Czerny 1980; Warner 1986, 1987) can be used in the UV, we obtain $L_{\rm disk} \geq 2.5 L_{\rm UV}$. If allowance is made for the unseen luminosity emitted below 1250 Å by extrapolating the average continuum up to 912 Å, one obtains $L_{\rm disk} \geq 130\ L_\odot$. A 1.4 $M_\odot$ white dwarf has a radius of about 0.004 $R_\odot$ (Hamada & Salpeter 1961). With the above reported values of $L_{\rm disk}$, M_2, and R_2, we derive a mass accretion rate $\dot{M} = 2.32 \times 10^{-8}\ M_\odot\ {\rm yr}^{-1} = 1.46 \times 10^{18}$ g s^{-1}.

Theory predicts (Tylenda 1981) that for an outer disk radius typical of a nova ($\sim 1\ R_\odot$), the disk becomes optically thick at accretion rates larger than 10^{17} g s^{-1}. If $R_{\rm out}$ is larger than 1 $R_\odot$ even at higher rates the outer disk remains optically thin. In T CrB the circularization radius for the material streaming off L_1 is $R_{\rm circ} = 0.6 P^{2/3}\ R_\odot = 22\ R_\odot$. We expect therefore a disk of much larger geometrical size than the usual disks in CVs, but optically thick only in the (hotter) innermost part. This is in agreement with the fact that in T CrB the disk emits mostly in the UV (which is also an indication that the white dwarf in the system is very massive), and with the estimates made in § 4.2 that the continuum-emitting region has radius less than 1 $R_\odot$. It is clear that the higher the accretion rate, the larger the size of the optically thick disk region. At higher rates also the cooler outer disk region will start emitting, thus contributing also to the ground U and to the visible. This scenario is consistent with the UV variability and with the episodical appearance in the optical region of a strong hot component (Joy 1938; Hachenberg & Wellmann 1939; Minkowski 1939; Walker 1957).

The hot continuum radiation produced in the inner disk and in the boundary layer ionizes the gas at the surface of the accretion disk, in the streams of material inside the volume of the Roche lobe, and in the giant's wind. Although the geometry is far from spherically symmetric, both for the central source(s) and the surrounding material, the physical conditions are somehow similar to those in a photoionized nebula, with a sequence of He II, He I, H II, and H I regions. It is commonly accepted that irradiation of the upper layers of the inner accretion disk by the EUV–soft X-ray radiation of the boundary layer is the mechanism mainly responsible for the presence of emission lines of high excitation in CVs. The emission intensity and the shape of the high-excitation UV emission lines of T CrB (He II λ1640, C IV λ1550) are in agreement with this picture (see §§ 4.8, 4.9, and 5.1) The variations in the emission-line intensities are related to the changes in the continuum since radiation is the main energy input mechanism. We lack optical observations of emission lines, but a comparison between the intensity of the UV continuum and that of the Hα emission (Anupama 1989) made at nearly the same epochs show a positive correlation between the two quantities.

A peculiarity of T CrB with respect to classical novae in quiescence is the presence of strong intercombination emission lines. This can be accounted for by the considerably larger volume of the Roche lobe (by a factor of about 10^6) which allows for the presence of a substantially large amount of gas at relatively low density. This gas can be associated to the wind of the giant star and to the outermost parts of the accretion disk. The emission lines and the continuum in T CrB are in general the result of two components: the accretion disk (responsible for the hot continuum and the rotationally broadened lines) and the low-density gas (responsible for the recombination continuum and the sharp components of the emission lines). The spectroscopic signatures of T CrB are therefore those of the old novae (high-excitation resonance lines and dominant disk continuum) with the addition of a nebular-like contribution (intercombination lines and gas continuum). The observed shape of the emission lines supports this model (see §§ 3.3 and 5.1).

Figure 10 and Table 4 illustrate the main features of the system.

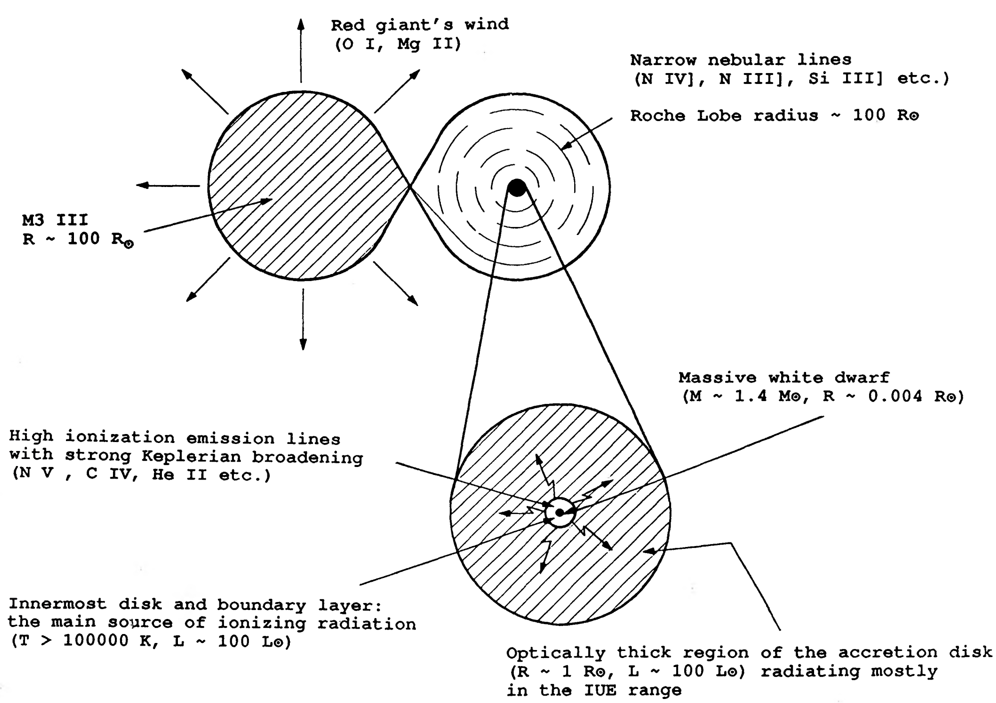

FIG. 10.—Schematic model of T CrB as inferred from the observations. See Table 4 for the relevant parameters.

TABLE 4

MAIN FEATURES OF THE SYSTEM

Parameter	Value
The Relevant Data from the *IUE* Observations	
Average UV luminosity	$40\ L_{\odot} \sim 1.5 \times 10^{35}$ ergs s^{-1}
Maximum UV luminosity	$70\ L_{\odot} \sim 2.7 \times 10^{35}$ ergs s^{-1}
Average continuum slope	$\alpha = 1.26$; $F_{\lambda} \sim \lambda^{-\alpha}$
Average He II (λ1640) luminosity	7×10^{32} ergs s^{-1}
HWZI (C IV λ1550)	$>1300(\sin i)^{-1}$ km s^{-1}; $i < 65°$ (no UV eclipses)
Mean electron density	2.8×10^{10} cm^{-3}
The Model	
Average disk luminosity	$120\ L_{\odot} \sim 4.5 \times 10^{35}$ ergs s^{-1}
Boundary layer luminosity	$\gtrsim 10^{35}$ ergs s^{-1}
Boundary layer temperature	$\sim 3.5 \times 10^{5}$ K
White dwarf mass	$\sim 1.4\ M_{\odot}$
White dwarf radius	$\sim 0.004\ R_{\odot}$
Average mass accretion rate	$2.32 \times 10^{-8}\ M_{\odot}\ yr^{-1} = 1.46 \times 10^{18}$ g s^{-1}
Giant's mass	$\sim 1.4\ M_{\odot}$
Roche lobe radius	$\sim 90\ R_{\odot}$
Giant's radius	$\sim 90\ R_{\odot}$

The absence of Fe II emissions in the spectrum of T CrB is intriguing. Most objects with similar spectral characteristics (e.g., symbiotic stars) usually show a very rich Fe II emission spectrum. Perhaps density effects prevent the formation of these lines. This seems supported by the fact that at several epochs, as reported in § 3.4, Fe II is present in absorption both in the far-UV region (from low-resolution data) and in the near-UV (from high-resolution spectra). It is not clear where the Fe II (and Ni II + Cr II) absorption lines are produced. They must originate from a rather cool region seen in front of the accretion disk, whose density must be rather high in order to populate Fe II (*lower*) levels as high as 8 eV. Some candidate regions (the outer disk seen edge-on, streams of gas near L_1 projected onto the disk, a portion of the giant's chromosphere projected onto the disk) seem to be ruled out on the basis of the system parameters and observational constraints. We can only tentatively suggest that the absorptions might originate from material surrounding the disk (a chromosphere-like region above the disk?) and rather close to it, with high density.

7. CONCLUSIONS

UV and other observations of T CrB during its quiescent phase have provided a wealth of data which finds a natural and self-consistent explanation if a white dwarf accretor rather than a main-sequence star is present in the system. The spectroscopic and photometric behavior of T CrB at the time of the 1946 outburst is not in contradiction with this conclusion and actually provides further support to a TNR event on a massive white dwarf. We stress that T CrB fully satisfies the criteria proposed by WLTO (1987) to identify a TNR recurrent nova from its behavior in quiescence and in outburst.

The *only* data which apparently contradict our conclusions are those of the emission-line radial velocities (Kraft 1958), but in § 5.1 we have pointed out that their measurement was (and is) intrinsically difficult and uncertain. If new and very accurate radial velocity measurements would confirm beyond any observational error that the companion of the giant is as massive as, say, $1.8\ M_{\odot}$, we feel that a possible explanation for the data could be sought in a triple system model for T CrB. The giant's companion could be a normal nova composed of a (massive) WD and a $0.5\ M_{\odot}$ low-luminosity main-sequence star practically undetectable in the giant's light. Note that the system composed by a giant plus an AM Her–like binary system has recently been discovered by Reimers (1985).

In our opinion, there is no alternative to the presence of a white dwarf in T CrB to explain its observed properties.

We are in debt to all those colleagues with whom, in recent years, we have discussed about the nature of T CrB. Special thanks are due to Mario Livio, Scott Kenyon, and Ron Webbink. We have enjoyed the stimulating conversations that on this argument we have had with them at various Conference sites, with pleasant "boundary conditions," e.g., Torun, Madrid, Santa Fè, and Vulcano Island. Without their remarks and criticism this paper would have appeared much sooner, although certainly much less complete. We must also acknowledge the authors of the paper reported as WLTO in the text. The content of their paper has been of great help in supporting our model, perhaps beyond the expectations of the authors.

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