1987ApJ...314..653W

THE ASTROPHYSICAL JOURNAL, **314**:653–672, 1987 March 15

THE NATURE OF THE RECURRENT NOVAE

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Received 1986 July 14; accepted 1986 September 3

ABSTRACT

The properties of the rather diverse members of the "class" of recurrent novae are reviewed, and points of similarity and differences are identified in an attempt to identify the probable mechanisms for their outbursts. We define specific criteria which distinguish recurrent novae from other objects and establish some general properties of thermonuclear runaway and accretion events by which the characteristics of individual recurrent nova systems can be evaluated. We then specifically review the properties of the individual systems and suggest an appropriate model for each one of them.

Two subclasses of recurrent novae are identified, according to their outburst mechanisms: (a) those powered by thermonuclear runaways on white dwarfs (T Pyx and U Sco), and (b) those powered by the transfer of a burst of matter from a red giant to a main-sequence companion (T CrB and RS Oph). V1017 Sgr, while strictly speaking a symbiotic star, may represent a hybrid case entertaining both thermonuclear runaways and accretion events. None of the remaining systems can be considered legitimate recurrent novae: WZ Sge, VY Aqr, RZ Leo, and V1195 Oph are dwarf novae; V616 Mon is a bright X-ray transient; and V529 Ori is of indeterminate nature.

Finally, we suggest identifying characteristics by which recurrent novae can be tentatively recognized even from a single outburst. Recurrent thermonuclear novae must have such low envelope masses that they must be emission-line objects even at maximum. The recurrent accretion-powered novae apparently require shock-type events to reach super-Eddington luminosities, and display very high excitation coronal-line emission during decline.

Subject headings: nucleosythesis — stars: binaries — stars: novae — stars: U Geminorum

I. INTRODUCTION

The recurrent novae (Payne-Gaposchkin 1957) collectively constitute a small class of objects which bear many similarities to other cataclysmic variable systems. They experience recurrent outbursts at intervals of ~20–80 yr, much longer than those characteristic of dwarf novae and much shorter than those estimated theoretically for the classical novae (for which only one outburst has thus far been observed). Early discussions of these phenomena were generally guided by the view that a common mechanism might be involved. We now know that all cataclysmic variables involve close binary systems and the necessity of significant mass transfer, but there the similarities may end. Both theoretical and observational studies now indicate that dwarf novae can be best understood in terms of accretion-powered events, while the outbursts of the classical novae are rather a consequence of thermonuclear runaways proceeding in the accreted hydrogen shells on the white-dwarf components of these close binary systems. We might therefore entertain both accretion and nuclear models for recurrent novae.

Payne-Gaposchkin (1957) specifically identified six of the seven best known members of the class of recurrent novae: T Coronae Borealis, RS Ophiuchi, WZ Sagittae, T Pyxidis, V1017 Sagittarii, and U Scorpii. VY Aquarii, which at that time was known to have experienced only a single (1907) outburst, was not included, but it was discussed elsewhere in her work. The observed properties of the systems she studied include the facts that both their recurrence periods (~20–80 yr) and their magnitude ranges in outburst (~7–11 mag) indeed place them intermediate between dwarf novae and classical novae. Their speed class designations span the range from slow (e.g., T Pyx) to very fast (U Sco, T CrB, and RS Oph are three of the very fastest known novae). Utilizing the Arp (1956) relation between maximum luminosity and rate of decline for classical novae, Payne-Gaposchkin then deduced values for both maximum and minimum absolute magnitudes for these systems. Since the Arp relation may not be applicable to the recurrent novae as a class, one should be extremely cautious in drawing conclusions from these numbers.

It will become apparent in the discussion to follow that those objects which have traditionally been labeled recurrent novae constitute a very heterogenous class of objects. In part, this is a result of a very loose definition of what constitutes a recurrent nova. We therefore propose that this designation be reserved to those systems satisfying the following criteria:

i) two or more distinct recorded outbursts, reaching absolute magnitude at maximum comparable with those of classical novae (i.e., $M_v \lesssim -5.5$), and

ii) ejection of a discrete shell in outburst, at velocities comparable with those of classical novae ($v_{\rm exp} \gtrsim 300$ km s^{-1}). The first criterion distinguishes recurrent novae from both classical and dwarf novae and also from symbiotic novae (Kenyon and Truran 1983). The second distinguishes them from the remain-

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ing symbiotic stars, many of which show bright, multiple outbursts, but without high-velocity shell ejection.

Our purpose in the present paper is to review the basic properties of individual recurrent nova systems and to seek to identify the mechanisms of their outbursts. As a prelude to these discussions we first briefly examine, in the next section, some general properties associated with accretion events and thermonuclear runaway models. In § III, we specifically discuss the observations and possible outburst models for the recurrent novae T CrB, RS Oph, T Pyx, U Sco, and V1017 Sgr. In addition, we examine and discuss other systems that have, at one time or another, been classified as recurrent novae; these include WZ Sge, V616 Mon, VY Aqr, RZ Leo, V1195 Oph, and V529 Ori. A general discussion, summary, and conclusions follow.

II. SOME GENERAL PHYSICAL CONSIDERATIONS

Before proceeding to discussions of the properties of individual systems, we seek first to identify some general properties of systems undergoing accretion-powered or nuclear-powered outbursts which we might be able to use to constrain models for specific recurrent novae.

Accretion events.—The situation regarding accretion-powered events is unsettled. While virtually everyone agrees, for example, that the dwarf nova eruptions are attributable to accretion events (see, e.g., Cordova and Mason 1983 and references therein), the nature of the underlying instability has not yet been unambiguously established. It is not clear whether instabilities associated with the red companion (e.g., Bath *et al.* 1974; Bath and Pringle 1981; Papaloizou and Bath 1975) or disk instabilities (Meyer and Meyer-Hofmeister 1983; Faulkner, Lin, and Papaloizou 1983; Mineshige and Osaki 1983; Cannizzo and Wheeler 1984; Smak 1984) are responsible for the outbursts (Hassall, Pringle, and Verbunt 1985). In addition to these mechanisms, there exist, among recurrent transient X-ray systems, examples (e.g., 4U 0114+63: Rappaport *et al.* 1978; A0538−66: Skinner *et al.* 1982) in which discrete mass transfer events are apparently triggered at periastron in an eccentric binary orbit. Let us consider each of these mechanisms in turn.

Dynamical instability of the red component, as a mechanism for modulating mass transfer, was first proposed by Paczyński (1965*a*), and later elaborated by Bath (1969, 1972). This phenomenon is theoretically capable of producing short bursts of mass transfer, provided that the outermost envelope of the donor star is dominated by superadiabatic convection. Its existence is related to the position and extent of the hydrogen and helium ionization zones. A limit-cycle type of behavior ensues in which the forces driving mass transfer on an evolutionary time scale (e.g., nuclear evolution of the donor star, or orbital decay due to gravitational radiation) compete against thermal relaxation within the donor star envelope, as it is repeatedly drained of its superadiabatic energy excess by mass transfer events. It is difficult to quantify the predictions of this model, because the calculation of hydrodynamic flow through the inner Lagrangian point, coupled with the dynamical response of the stellar interior, is not yet a fully tractable problem (Bath 1975; Gilliland 1985; Edwards 1985). Nevertheless, there is direct observational evidence that pulsed mass transfer does occur in some Algol-type binaries (Olson 1985). Qualitatively, we may expect this type of behavior from stars lying on or near the Hayashi limit in the Hertzsprung-Russell diagram, provided that they are not so low in luminosity that convection is nearly adiabatic throughout (cf. Papaloizou and Bath 1975; Wood 1977). Whether mass transfer is pulsed, or proceeds immediately to strip the entire envelope of the donor star (see e.g., Paczyński and Sienkiewicz 1972), also depends on the relationship between the adiabatic stellar response to mass loss, and the dynamical response of the Roche lobe to mass transfer (see Webbink 1985).

Models of disk instabilities now rest on a somewhat more secure quantitative basis. Physically, the mechanism responsible for this instability, as it applies to dwarf novae, is closely related to that responsible for mass transfer instabilities in a cool donor star discussed above, namely, the rapid drop in stellar opacities below hydrogen ionization temperatures. Equilibrium disks with surface temperatures immediately below a critical value,

$$\log T_{\rm crit}(r) = 3.81 - 0.0767 \log (r/R_\odot) \tag{1}$$

(Meyer and Meyer-Hofmeister 1983; a solar mass accretor is assumed), are thermally unstable—the rate of viscous energy generation is a decreasing function of the surface density of the disk. (In eq. [1], r is the radius of the disk.) There exists a lower temperature threshold for instability as well, but its value is still a matter of controversy. The equilibrium disk temperature is in turn related to the mass-accretion rate, $\dot{M}$, by the expression

$$T(r) = \left(\frac{3GM\dot{M}}{8\pi\sigma R_*}\right)^{1/4}\left(\frac{R_*}{r}\right)^{3/4}\left[1 - \left(\frac{R_*}{r}\right)\right]^{1/4} \tag{2}$$

(see e.g., Shakura and Sunyaev 1973), where M is the mass of the accretor and R_* the radius of the accreting star. Since $T(r)$ decreases rapidly with r, a stable equilibrium disk with decreasing $\dot{M}$ will first become unstable at its outer radius (although the same statement may not be true of nonequilibrium disks), and limit-cycle behavior will ensue. If we thus equate r with the ballistic outer disk radius,

$$R_D \approx 0.072A(q + q^2)^{1/4} \tag{3}$$

(Ulrich and Burger 1976, after Lubow and Shu 1975), where A is the binary separation and q the mass ratio (accretor/donor), we obtain an estimate for the critical mass-transfer rate above which the disk instability is suppressed:

$$\dot{M}_{\rm crit} \approx (3 \times 10^{-9}\ M_\odot\ {\rm yr}^{-1})(P/d)^{1.98}\ , \tag{4}$$

where we have assumed a solar mass accretor of vanishingly small radius, and a mass ratio unity. For $\dot{M} < \dot{M}_{\rm crit}$, we may therefore expect disk instability to occur. The subsequent viscous evolution of the disk has been calculated by the various authors cited above, for conditions appropriate to dwarf novae, and by Duschl (1986*a*, *b*), for conditions appropriate to symbiotic stars.

Finally, we may expect the rate of mass loss from a lobe-filling star to be strongly modulated by orbital eccentricity if that eccentricity exceeds the ratio of the pressure-scale height at the inner critical surface at periastron to the radius of the lobe-filling star (see the explicit calculation of $\dot{M}$ as a function of radius excess in Paczyński and Sienkiewicz 1972). This modulation could be greatly amplified if the mass-losing star were unstable to the superadiabatic mechanism discussed above. However, theoretical estimates of the orbital circularization time scale due to eddy viscosity for stars with deep convective envelopes (see e.g., Zahn 1977) give values which are significantly shorter than the evolutionary growth time scales

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for even very luminous asymptotic giant branch stars (see Fig. 1 in Webbink, Rappaport, and Savonije 1983). This implies that the orbits of late-type stars can have little residual eccentricity by the time those stars fill their Roche lobes. Nevertheless, the tendency of a few long-period binaries to exhibit outbursts correlated at specific orbital phases (see the discussion of T CrB below; also the light curve of the symbiotic star CI Cyg by Belyakina [1983]) suggest that significant departures from circular orbits (perhaps induced by mass-transfer episodes themselves) may yet occur in long-period systems.

Thermonuclear runaways.—In view of the success achieved in explaining classical novae (see, for example, Gallagher and Starrfield 1978; Truran 1982), it is appropriate to consider whether any of the members of the class of recurrent novae might involve a thermonuclear runaway event. In this instance, some severe theoretical constraints are available. The basic challenge is of course to be able to achieve recurrence periods as short as ~20–80 yr in the context of a thermonuclear runaway model; the requirement is that the necessary amount of matter be accumulated on the white dwarf to trigger ignition under sufficiently degenerate conditions for a runaway to ensue.

The critical parameter which determines the strength of the outburst is the pressure at the base of the accreted envelope (Fujimoto 1982; Prialnik *et al.* 1982; MacDonald 1983). The basic problem in obtaining very short recurrence periods originates from the fact that at very high accretion rates ($\dot{M} \gtrsim 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$ for $M_{\mathrm{wd}} \lesssim 1\ M_\odot$), which are accompanied by rapid compression and relatively inefficient cooling of the envelope, ignition occurs under only mildly degenerate conditions and, as a consequence, only a weak flash is obtained (see also Kutter and Sparks 1980). The only way to avoid the necessity of accretion rates so high that they would suppress the strength of the outburst is to accrete onto a white dwarf with a mass close to the Chandrasekhar limit. Due to the fact that the pressure at the white dwarf envelope interface

$$P \approx \frac{GM_{\mathrm{wd}}\Delta M_{\mathrm{acc}}}{4\pi R_{\mathrm{wd}}{}^4} \tag{5}$$

(where ΔM_{acc} is the mass of the accreted envelope), is sensitively dependent on the white dwarf mass (see Truran and Livio 1986 for discussion), a significantly smaller envelope mass is required for ignition in such a case. This, in turn, allows smaller accretion rates to produce outbursts on the required time scale.

Another parameter which can affect the ignition conditions is the intrinsic white dwarf luminosity. Increasing it serves to increase the temperature at the base of the envelope and thereby reduce the envelope mass required for ignition. Indeed, for a limiting mass white dwarf $M_{\mathrm{wd}} = 1.38\ M_\odot$, of luminosity $L_{\mathrm{wd}} = 0.1\ L_\odot$, Starrfield, Sparks, and Truran (1985) were able to obtain an outburst after only 33 yr for an accretion rate $\dot{M} = 1.7 \times 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$.

Following a brief super-Eddington phase characteristic of the fastest novae, a post-runaway nova white dwarf experiences a phase of shell hydrogen burning (which continues through the exhaustion of the nuclear fuel) at a luminosity compatible with the core mass-luminosity relation (Paczyński 1971)

$$L/L_\odot \approx 59250(M_{\mathrm{wd}}/M_\odot - 0.522)\ . \tag{6}$$

For massive white dwarfs this luminosity approaches the Eddington limit,

$$L_{\mathrm{Edd}}/L_\odot \approx 3.8 \times 10^4(M_{\mathrm{wd}}/M_\odot)\ . \tag{7}$$

Since the recurrent nova systems with which we are concerned must almost certainly involve very massive white dwarfs, if a thermonuclear runaway model is to be appropriate, we can to a good approximation then simply argue that the luminosity at maximum must be given by

$$L_{\max} \gtrsim L_{\mathrm{Edd}}\ . \tag{8}$$

The high accretion rate demanded to replenish the envelope on the recurrence time scale also serves to impose a constraint on the system luminosity at minimum. The total implied luminosity for a 1.38 $M_\odot$ white dwarf is

$$\frac{L_{\mathrm{bol}}}{L_\odot} = \frac{GM\dot{M}}{R} \approx 160\,\frac{(M_{\mathrm{wd}}/1.38\ M_\odot)}{(R_{\mathrm{wd}}/1.9 \times 10^8\ \mathrm{cm})}\,\frac{(\dot{M})}{(10^{-8}\ M_\odot\ \mathrm{yr}^{-1})}\ . \tag{9}$$

If one further assumes accretion to proceed via disk, the implied absolute visual magnitude at quiescence is given by (see Appendix)

$$M_V = -9.48 - \frac{5}{3}\log\left(\frac{M}{M_\odot}\,\frac{\dot{M}}{M_\odot\ \mathrm{yr}^{-1}}\right) - \frac{5}{2}\log\,(2\cos i)\ , \tag{10}$$

where i is the inclination of the orbital axis to the line of sight to the observer.

We have thus identified two important constraints upon the absolute magnitude of recurrent novae at maximum and at quiescence—assuming that their outbursts are a consequence of thermonuclear runaways. These allow the possibility of improved distance estimates, an important result for systems viewed at relatively high galactic latitudes. The two constraints together must also be compatible with the observed magnitude range for the recurrent nova system in question.

III. INDIVIDUAL SYSTEMS

a) T Coronae Borealis

($\alpha_{1950} = 15^{\mathrm{h}}57^{\mathrm{m}}24^{\mathrm{s}}.505,\ \delta_{1950} = +26^\circ03'39''.04$)

T CrB (=HR 5958 = HD 143454 = BD +26°2765) has undergone two recorded outbursts, in 1866 and 1946.[2] These two outbursts appear to have been virtually identical in their time development, each reaching approximately $m_v \approx 2.0$ (see Campbell and Shapley 1923; also Kamenchuk 1947). They are remarkable not only for their exceptionally rapid rise to and decline from maximum, but also for the appearance, at nearly precisely the same time interval after primary maximum in each case, of a secondary maximum, reaching $m_v \approx 8.0$ (Pettit 1946).

In its quescent state ($V \approx 10.2$), the spectrum of T CrB is dominated by an M3 III giant (Adams and Joy 1921; Berman 1932). Radial velocity variations of this star were first detected by Sanford (1949), who found an orbital period of $230^{\mathrm{d}}.5$, and

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[2] A possible outburst in autumn 1217 has been uncovered by Botley (1967). We are inclined to reject this interpretation, as the original account implies that the object in question was visible to the naked eye both before and after outburst. However, there are no known large-amplitude naked-eye variables in this region of the sky. Sir John Hershel (1866) reported having possibly seen T CrB in outburst on 1842 June 9. However, McLaughlin (1939) notes that the position on Herschel's published chart is discrepant by fully a degree, and accords much better with that of BD +25°3020 (G8 V, $V = 7.10$), which might be perceptible to the naked eye under the most favorable observing conditions.

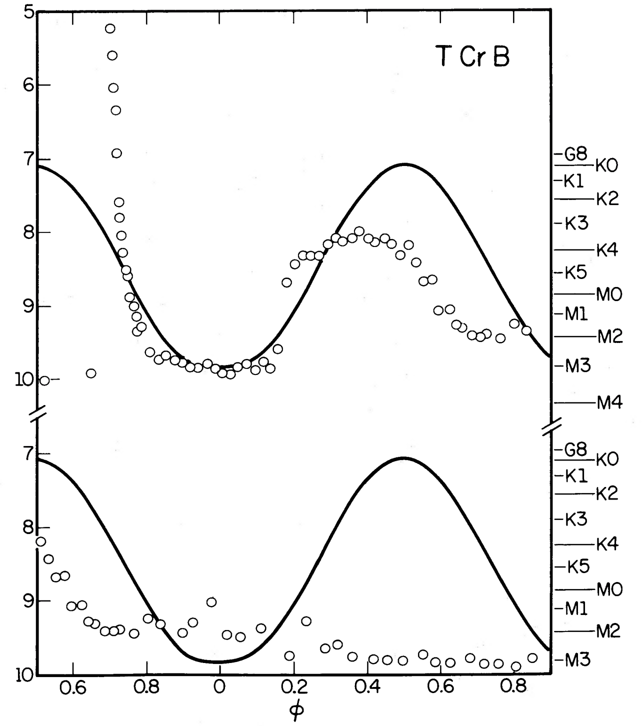

FIG. 1.—The 1946 outburst of T CrB. Two full orbital cycles are plotted. The open circles correspond to 1, 5, or 10 day means of observations reported by members of the AAVSO (Campbell 1948; Mayall 1950*a*, *b*; 1951*a*, *b*, *c*). The continuous curve is the theoretical visual light curve arising from the M3 III giant heated by a Chandrasekhar mass companion radiating at Eddington luminosity. A bolometric albedo $\alpha = 0.5$ has been assumed. The mean spectral type of the visible hemisphere of the heated giant is indicated on the right-hand vertical axis. The post-maximum observational points clearly do not follow model predictions.

velocity amplitude $K_1 = 21$ km s^{-1}. His orbit was later refined by Kraft (1958), who determined an orbit for the hot component as well, by Paczyński (1965*b*), and, most recently by Kenyon and Garcia (1986). The spectroscopic orbital parameters of T CrB are listed in Table 1. The spectroscopic orbit of the giant is quite accurately known, whereas that of its hot companion is based on only seven velocities of modesty accuracy. Nevertheless, the deduced mass ratio (and hence the values of $M \sin^3 i$ for each star) is indirectly supported by the amplitude of the ellipsoidal disturbance to the velocity curve of the giant (Kenyon and Garcia 1986).

TABLE 1

SPECTROSCOPIC ORBIT OF T CORONAE BOREALIS[a]

Parameter	Value
T_0[b]	JD 2,431,933.83 ± 0.13
P	227.53 ± 0.02 days
V_0	-27.89 ± 0.06 km s^{-1}
K_1	23.32 ± 0.16 km s^{-1}
K_2	33.76 ± 3.21 km s^{-1}
$M_1 \sin^3 i$	2.60 ± 0.54 $M_{\odot}$
$M_2 \sin^3 i$	1.80 ± 0.20 $M_{\odot}$
$a \sin i$	$257. \pm 14.$ $R_{\odot}$

[a] Subscript 1 refers to the M3 III star, 2 to its hot companion. Values quoted for T_0, P, V_0, and K_1 are from Kenyon and Garcia (1986); K_2 from a fit of Kraft's (1958) velocities assuming T_0, P, and V_0 from this table. Standard errors are quoted.

[b] Epoch of inferior conjunction of the M3 III star.

Photometrically, T CrB is now known to be an ellipsoidal variable at visual wavelengths (Bailey 1975*a*). Although T CrB is not known to be eclipsing, the amplitude of the ellipsoidal variations is quite large ($\gtrsim 0.3$ mag at V), and the hot component contributes very little to the total light of the system beyond ~ 5000 Å, so eclipses would be difficult to detect. (At shorter wavelengths, the orbital modulation of the light curve is masked by the much more rapid variability of the hot component.) Given the spectroscopic mass ratio, grazing eclipses (for a point mass hot component and lobe-filling giant) would occur for an orbital inclination $i = 66\overset{\circ}{.}97 \pm 0\overset{\circ}{.}57$, which is essentially the orbital inclination adopted by Kraft (1964) and Paczyński (1965*b*); in this case, the corresponding masses for cold and hot components are 3.34 ± 0.73 $M_{\odot}$ and 2.31 ± 0.29 $M_{\odot}$, respectively.

The large lower mass limit deduced for the hot component, exceeding the Chandrasekhar limit for any orbital inclination, has long been recognized as a problem for thermonuclear models of its outburst, which presume it to be a white dwarf. This prompted the suggestion (Plavec, Ulrich, and Polidan 1973; Harmanec 1974) that the hot component is more likely a main-sequence star, with the cool giant on the brink of dynamical time scale mass transfer. Webbink (1976) showed than an accretion-powered outburst model based on such a system configuration could account for the time scale, energetics, and peculiar photometric structure of the outbursts of T CrB.

Briefly stated, the accretion model proposed by Webbink attributes the principal maximum in the outbursts of T CrB to the dissipation of the excess energy of a parcel of transferred mass (estimated to be of order $\Delta M \approx 5 \times 10^{-4}$ $M_{\odot}$) as it collapses (via highly supersonic collisions with itself, as it is drawn out into a stream) into a circular orbit about the accreting star. As shown by Livio, Truran, and Webbink (1986) for the very similar system RS Ophiuchi (see below), the density contrast between the stream and the outflowing stellar wind of the giant is sufficient to accelerate the shock waves thus formed to velocities approaching 10^4 km s^{-1}, high enough to account for the velocities observed in T CrB immediately after maximum (see, for example, the discussion by Payne-Gaposchkin [1957]). This principal maximum is followed, 106 days later, by a brightening to a secondary maximum. In the model, this secondary maximum is powered by the accretion onto the companion of the ring formed in the principal maximum. The time delay between principal and secondary maxima then establishes the viscous time scale of the disk, and the ratio of the amplitude of the secondary maximum to the integrated energy output of the principal maximum reflects the depth of the gravitational potential at the surface of the accreting star. Webbink (1976) showed that these quantities are in good agreement with estimates of viscous time scales in other disk accretors, and that the surface potential of the accreting component is that of a main-sequence star (as indicated by the spectroscopic mass function), and not a white dwarf.

Webbink (1976) did not discuss the spectroscopic development of the outbursts of T CrB, but there are several features of that development which point unmistakably to an accretion event, as described, and *not* to a thermonuclear runaway. In chronological order, they are the following.

Spectrum prior to outburst.—Some 8 months prior to the 1946 outburst, Leslie Peltier, a member of the AAVSO who had monitored T CrB visually since 1919, announced an unprecedented *decline* in the apparent magnitude from its normal value, $m_v = 9.83$ on Peltier's photometric scale, to $m_v = 10.8$ on 1945 May 20 and 28 (Peltier 1945; Mattei 1976*b*). A spectrum secured on 1945 June 19, by which time the system had recovered to $m_v = 10.5$, showed a strong M-type continuum, with the Balmer emission lines much weaker than normal and He II λ4686 emission absent or very weak (Sahade 1945). This brightness minimum must be associated with a dimming of the giant component, which dominates the light of this system at minimum. Webbink (1976) speculated that it marked the dynamical ejection by the giant of the parcel of mass later giving rise to the principal maximum.[3] Regardless of whether this speculation is correct, the spectrum obtained by Sahade clearly indicates that only traces of an accretion disk, at most, were present in T CrB immediately preceding its outburst. This situation is consistent with the needs of a circularization model for the principal maximum, in which the preexistence of a substantial accretion disk would smear out the energy dissipated by circularization. It contrasts sharply with Robinson's (1975) findings that classical novae differ little between preoutburst and postoutburst states, with fast novae showing, if anything, a tendency to *increase* slightly in brightness immediately preceding eruption.

Bolometric decline from principal maximum.—Theoretical models of thermonuclear outbursts predict, and observations confirm, that classical novae remain bright bolometrically long after optical decline (see, e.g., Gallagher and Starrfield 1978). A bolometric plateau occurs at the stable shell burning luminosity corresponding to the white dwarf mass, and only marginally below the Eddington limit, with the excess radiation (over the visible luminosity) appearing either in the ultraviolet, or, in cases of optically thick grain formation (as in the great minimum of DQ Her), in the infrared. T CrB, in distinct contrast, apparently never reached a bolometric plateau during its decline from principal maximum. We lack contemporaneous ultraviolet or infrared observations, but the evidence at hand, while circumstantial, is nonetheless compelling: During the interval between principal and secondary maxima, the spectrum of the M3 giant is clearly visible, and appears remarkably undisturbed (cf. Bloch *et al.* 1946; Deutsch 1948; Sanford 1949). There can be no doubt that the absorption spectrum seen during this interval was that of the giant component, as it displays the orbital radial velocity variations of that star completely undisturbed (Sanford 1949). This at once tells us that this intervening minimum was *not* produced by dust enveloping the entire system, as in classical novae such at T Aurigae and DQ Herculis, which show deep minima during their decline. Neither can a large luminosity be hidden in the ultraviolet: Such a source would be readily revealed through its severe heating of the facing hemisphere of the M giant companion (see Fig. 1). Both outbursts of T CrB have occurred at singularly unfavorable orbital aspects for the detection of this effect, with inferior conjunction of the M giant, when its heated hemisphere faces away from Earth, occurring midway between principal and and secondary maxima. Nevertheless, the abrupt decline from principal maximum, unmitigated by heating effects on the companion (then near greatest elongation)—note the 0.5 mag luminosity deficit at phase 0.81 in Figure 1—place an upper limit of $1 \times 10^4\ L_\odot$ on the luminosity of the hot component at this point, a factor of 5 below the expected plateau luminosity.

Spectrum during secondary maximum.—Among classical novae showing distinct primary and secondary maxima (as distinguished from the multiple maxima of very slow novae which fluctuate randomly near maximum), the secondary maximum is generally associated with the dissipation of the circumstellar dust responsible for the intervening minimum (Hyland and Neugebauer 1970; Geisel, Kleinmann, and Low 1970; Gallagher 1977; Bode and Evans 1982, 1983). Invariably, the secondary maximum is characterized by a strong nebular spectrum (see e.g., McLaughlin 1960). In contrast, T CrB displays quite the opposite behavior: It is the *continuum* which strengthens markedly during secondary maximum, nearly overwhelming the circumstellar emission (Bloch *et al.* 1946; Sanford 1949; McLaughlin 1953). Although the rise to secondary maximum coincides in orbital phase roughly with the reappearance of the inner hemisphere of the giant, an explanation in terms of the reflection effect is excluded both by the absence of such an effect at the preceding complimentary phase, as noted above, and by the color of the system during secondary maximum. A comparison of available photographic light curves (Taffara 1949; Betti and Rosino 1952; Weber 1961) indicates a color index C.I. $\approx +0.45 \pm 0.1$ at secondary maximum, or $(B-V)_0 \approx +0.4$ in the Johnson system, after correcting for interstellar reddening ($E[B-V] = 0.15$; Cassatella *et al.* 1982). This is much bluer than $(B-V)_0 \approx +1.35$, expected from the reflection effect (Fig. 1), corresponding instead to the color of an early F supergiant contaminated by a small contribution from the M giant. The secondary maximum thus corresponds to a true bolometric maximum. Its general properties (strong continuum, early F colors) are typical of the accretion disks seen in outbursting accretion-powered symbiotic stars (Kenyon and Webbink 1984).

Emission-line profiles in quiescence.—Kraft (1958) was able to subtract the underlying M giant continuum from the region around Hβ and Hα in spectra he obtained of T CrB in 1956 June and 1957 June, respectively. The reconstructed emission-line profiles are illustrated in Figure 2 of his paper and show unmistakably the doubled structure characteristic of an accretion disk (see, e.g., the models of Smak [1981]). In contrast with the very broad wings expected from a disk surrounding a massive white dwarf, however, Kraft's profiles extend to only very modest velocities: half widths at zero intensity of only 240 km s^{-1} and 370 km s^{-1} for Hβ and Hα, respectively. These velocity widths are in fact much more characteristic of Keplerian motion near the surface of a main-sequence star.

Ultraviolet continuum in quiescence.—At minimum, the ultraviolet flux distribution of T CrB is relatively weak, and highly variable (Krautter *et al.* 1981; Cassatella *et al.* 1982). Kenyon and Webbink (1984) attempted to fit the *form* of the flux distribution to their model ultraviolet continua but were unable to find a consistent model in light of the variability. As discussed by Kenyon and Garcia (1986), however, this failure undoubtedly reflects the fact that the disk was optically thin in the ultraviolet at the times of observation. They point out, on the other hand, that the total ultraviolet luminosity is quite small ($L_{uv} \sim 5$–$40\ L_\odot$ for a distance of 1400 pc; Cassatella *et al.*

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[3] The time interval between this minimum and principal maximum, $\Delta t \approx 263$ days, is consistent with the thermal diffusion time scale, $\Delta t_{\rm diff} \approx \pi R_L/2c_s$, for gas ejected by the giant to disperse through its entire orbit about the accreting star. (R_L in this expression is the Roche lobe radius of the accreting star, $R_L \approx 6.4 \times 10^{12}$ cm in T CrB, and c_s the photospheric sound speed of the M3 giant, $c_s \approx 4.4$ km s^{-1}; together, these values give $\Delta t \approx 262$ days.) Since the orbit of this matter is nonperiodic in a binary system, its closure by diffusion leads to internal collisions—and collapse into a ring.

1982; Cassatella, Gilmozzi, and Selvelli 1985), implying an accretion rate of $\sim 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$ for a white dwarf accretor, or $\sim 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$ for a main-sequence accretor. At this accretion rate a white dwarf accretor would produce He II $\lambda 1640$ and $\lambda 4686$ emission far stronger than that observed. By the same token, the significantly lower accretion rate onto a white dwarf thus implied would effectively exclude the possibility of refueling a thermonuclear runaway model within 80 yr.

We conclude, therefore, that an accretion model for the outbursts of T CrB provides a suitable framework for the interpretation of this system, in both its photometric and its spectroscopic development. It is curious to note, in this regard, that a mass-transfer model is also suggested by the fact that the two documented outbursts of T CrB occurred at precisely the same orbital phase, within the accuracy of its orbital ephemeris. That in 1866 can be pinpointed as having occurred not more than 4 hr prior to its discovery by J. Birmingham on JD 2,402,734.53 (see Lynn 1866). The outburst in 1946 seems to have been first sighted by A. S. Kamenchuk (1947) on JD 2,431,860.3. Kamenchuk made his observation at Shimanovsk, in Eastern Siberia. At the time, T CrB was just becoming visible before dawn, and Kamenchuk was at an advantage in being located at a relatively northern latitude. Given the large number of independent discoveries of T CrB made within the subsequent 16 hr it seems unlikely that the outburst had yet appeared when dawn came to the west coast of North America, ~ 5 hr before Kamenchuk's discovery. The orbital phases, computed from the parameters of Table 1, of Birmingham's 1866 and Kamenchuk's 1946 discovery observations, are $\phi = 0.668 \pm 0.011$ and $\phi = 0.677 \pm 0.001$, respectively, 128 orbital periods apart.

b) RS Ophiuchi

$\alpha_{1950} = 17^{\mathrm{h}}47^{\mathrm{m}}31^{\mathrm{s}}.53, \delta_{1950} = -6°41'39''.7)$

RS Oph (= HD 162214 = BD −6°4661) is, in many respects, a sister system to T CrB. It has undergone recorded outbursts in 1898, 1933, 1958, 1967, and 1985, reaching an average peak magnitude of $m_v \approx 4.6$, from its normal mean magnitude at minimum, $m_v \approx 11.5$. Its outbursts follow a pattern very similar to those of the T CrB, with exceptionally high ejection velocities at maximum, decaying to more modest velocities during decline, and developing high-excitation forbidden (coronal) emission-line spectrum during late decline (see, e.g., Bloch and Dufay 1958; Folkart, Pecker, and Pottasch 1965; Tolbert, Pecker, and Pottasch 1967; Barbon, Mammano, and Rosino 1968). As in T CrB, the light curve evolves on a very rapid time scale, though not so rapid as T CrB itself. The similarities between these objects apparently extend as well to the parameters characterizing the underlying systems: RS Oph contains an M0–M2 III giant (Sanduleak and Stephenson 1973; Barbon, Mammano, and Rosino 1968) for which Garcia (1986) has recently derived a 230 day orbital period.

The outbursts of RS Oph do differ from those of T CrB in one important respect, however: they show no vestiges of a secondary maximum. This difference led Livio, Truran, and Webbink (1986) to propose a variation of the model described above for T CrB in the case of RS Oph, one in which the parcel of mass transferred from the giant strikes the accreting stars directly, rather than first forming an accretion disk. RS Oph has thus evolved further toward runaway dynamical time scale mass transfer than T CrB, and as a result, has more frequent outbursts and an accreting star which has become bloated well beyond its normal main-sequence dimensions, due to a tenfold higher mean mass-transfer rate. Indeed, its inflated luminosity has become comparable with, or somewhat greater than, that of the M giant at minimum, unlike T CrB, in which the giant dominates the visible light at minimum.

We shall forego here a detailed discussion of RS Oph along the same lines as the other recurrent novae—the reader is referred to the paper by Livio, Truran, and Webbink (1986) for a detailed account of the strengths and weaknesses of thermonuclear runaway and accretion models for the outbursts of this system. As with T CrB, the most severe problem for thermonuclear models is that, in quiescence, upper limits to the hard ultraviolet flux derived from the weakness of high-excitation features such as He II $\lambda 4686$ already lie two or more orders of magnitude below that expected from accretion onto a massive white dwarf at rates sufficient to refuel outbursts at the observed recurrence rate. Accretion models, in turn, must appeal to dynamical phenomena, rather than viscous disk accretion, to accommodate the very rapid evolution of the principal maximum and the high initial ejection velocities. Livio, Truran, and Webbink show that these features can be reproduced quantitatively for the accretion model described above.

c) T Pyxidis

$(\alpha_{1950} = 09^{\mathrm{h}}02^{\mathrm{m}}37^{\mathrm{s}}.151, \delta_{1950} = 32°10'47''.41)$

T Pyxidis is perhaps the most regular member of the class of recurrent novae: it is known to have experienced outbursts in 1890, 1902, 1920, 1944, and 1966, with a correspondingly short mean interval between outbursts of $\bar{\tau}_{\mathrm{rec}} = 19$ yr. It is also distinguished by the extremely slow development of its optical light curve, in outbursts which themselves appear remarkably similar from event to event. The 1966 outburst required 32 days to reach maximum light, exhibited a relatively flat maximum, and then declined at a rate of 0.034 mag day^{-1}. (Payne-Gaposchkin [1957] determined 0.032 mag day^{-1} as a mean for the 1902, 1920, and 1944 outbursts.) An oscillatory behavior was evident in the visual light curve during the later stages of decline, ~ 50–70 days after maximum, seemingly analogous to the transition stage in the development of the classical novae.

There are a number of other features associated with the outbursts of T Pyx which are also of interest. Catchpole (1969) identified absorption features at $v \approx 850\ \mathrm{km\ s^{-1}}$ with the "principal ejecta," by analogy with classical novae, while further absorption groups indicating velocities up to $\sim 2000\ \mathrm{km\ s^{-1}}$ were also present. Catchpole (1969) further notes that the absence of significant absorption lines other than those of hydrogen, together with variations in the spectroscopic development, make it difficult to compare T Pyx with classical nova events (see also Chincarini and Rosino 1968). High-excitation features are also evident, as is the case for the recurrent novae T CrB and RS Oph, the outbursts of which probably represent accretion events (Webbink 1976; Livio, Truran, and Webbink 1986). Finally, while Catchpole (1969) found no evidence for the presence of surrounding gas, T Pyx has subsequently been found to be surrounded by a discernible nebular shell (Duerbeck and Seitter 1979; Williams 1982) and an even larger, faint extended hydrogen envelope (Shara 1985).

Critical system parameters.—Factors critical to an understanding of the nature of the outbursts of T Pyx include the luminosities at minimum and maximum and the colors. Scrutiny of the literature leads us to adopt the mean values: $\bar{V}_{\mathrm{min}} = 15.23$, $(\bar{B}-\bar{V})_{\mathrm{min}} = +0.099$, $(\bar{U}-\bar{B})_{\mathrm{min}} = -0.99$, $(\bar{V}-\bar{R})_{\mathrm{min}} = +0.175$ (Landolt 1977*a*; Mumford 1971), and, for the outbursts of T Pyx, $\bar{V}_{\mathrm{max}} = 7.0$ (Catchpole 1969; Eggen, Mathewson, and Serkowski 1967; Mayall 1967). The extinction has been estimated as $A_v = 1.12$ on the basis of the 2200 Å feature (Bruch, Duerbeck, and Seitter 1981). This corresponds to a reddening $E_{B-V} = 0.36 \pm 0.05$, yielding corrected colors $(B-V)_0 = -0.26$, $(U-B)_0 = -1.25$, and $(V-R)_0 = -0.11$. The colors are consistent (within the uncertainties in reddening) with an infinite temperature blackbody. A critical point here is the fact that, for any reasonable choice of the distance to the system, the absence of a $V-R$ excess excludes the possibility that T Pyx contains a luminous red giant, as in T CrB or RS Oph (see below). Rather, T Pyx must be much shorter in orbital period, more similar to dwarf novae or classical novae.

Determination of the absolute magnitude and luminosity of the system in outburst and at quiescence requires a knowledge of the distance and the reddening. A critical observation here is provided by the fact that a recent photograph (Shara 1985), shows no significant expansion of the shell since Williams's (1982) observations of 1981. This implies that the visible shell probably does *not* represent ejecta from the 1966 outburst, but presumably from some earlier event or combination of events, and that the distance in this case cannot be less than ~1 kpc. No distance information is obtained if, on the other hand, the visible shell is a standing shock (though we note here that the shell appears to be photoionized [Williams 1982], and not collisionally ionized, as we might expect in this case). The distance quoted by Catchpole (1969) of 1050 pc, which is based on the equivalent width of the interstellar calcium K line, must also be regarded as a lower limit for an object so far from the galactic plane ($b = +9^\circ.70$). The very slow development of the light curve, on the other hand, and particularly the leisurely approach to maximum (see, e.g., Mayall 1967; Eggen, Mathewson, and Serkowski 1967), indicate that the luminosity of T Pyx at maximum cannot much exceed the Eddington limit. Otherwise, radiation pressure would have forced a much more rapid expansion of the photosphere, as seen in fast classical novae. We can therefore regard the absolute magnitude at maximum derived from the rate-of-decline relationship for classical novae $(M_v)_{\max} = -7.4$ (Duerbeck 1981), itself marginally super-Eddington, as a plausible limit. The mean observed magnitude at maximum ($\bar{V}_{\max} = 7.0$), plus the extinction adopted above then give $D = 4500$ pc as an upper limit.

In the following discussion, we shall adopt, as the true distance modulus of T Pyx, the value $(m - M)_0 = 11.7 \pm 1.6$, the mean of the upper and lower limits deduced here (1050–4500 pc), with the quoted uncertainty extending to both of those limits. This implies a mean visual luminosity at maximum, $\log (L_v)_{\max}/L_\odot = 4.2 \pm 0.6$. Integrating over the optical light curve, we obtain for the total *visual* energy released in outburst, $\log E_v(\text{ergs}) = 44.4 \pm 0.6$, where the nominal error in this quantity again reflects uncertainty in the distance to T Pyx. In comparison, the visual energy radiated between outbursts amounts to ~0.08 of the outburst energy: The absolute visual magnitude and luminosity for the system at minimum, using our adopted $\bar{V}_{\min} = 15.23$, are $(M_v)_{\min} = +2.4 \pm 1.6$ and $\log (L_v)_{\min}/L_\odot = 0.9 \pm 0.6$, respectively.[4] From the dereddened $V-R$ color at minimum, we estimate further that the cool component can contribute no more than 10% of the flux at R at minimum; given our upper limit for the distance to T Pyx, this limits the bolometric luminosity of that component to $L_2 \lesssim 2\, L_\odot$, and the orbital period for such a lobe-filling star to $P \lesssim 3^{\rm d}$. With these estimates in hand, we can now proceed to explore possible outburst models.

Outburst behavior.—We note first, following our earlier discussion, that the most reasonable and advantageous choice of the white-dwarf mass in a thermonuclear runaway model is one approaching the Chandrasekhar limit—this ensures the shortest possible recurrence time for any specified accretion rate (which is necessary to obtain $\tau_{\rm rec}$ as short as 19 yr). In this model, nuclear burning in outburst typically proceeds at a luminosity approaching the Eddington limit, $L_{\rm Edd}/L_\odot = 3.8 \times 10^4 M/M_\odot$. For white-dwarf masses of order the Chandrasekhar mass, $M \sim 1.4\, M_\odot$, this would of course place T Pyx near the upper limit of the range of possible distances deduced above. The slow rise of T Pyx to maximum is reminiscent of that of very slow classical novae, such as HR Del and RR Pic, which show the same sort of fluctuations in their light curves near maximum as does T Pyx. During that rise to visual maximum, the broad-band colors of T Pyx become *redder*, with $(B-V)_{\max} = +0.31$, $(U-B)_{\max} = -0.08$ (Eggen, Mathewson, and Serkowski 1967). This behavior is characteristic of an expanding photosphere and typical of classical novae. The corresponding dereddened colors, $(B-V)_{0,\max} = -0.05$, $(U-B)_{0,\max} = -1.06$, are, however, bluer (especially in $U-B$) than a typical nova at maximum; but T Pyx has already developed prominent emission lines at this stage (Catchpole 1969). As noted above, the appearance of a number of velocity systems during the course of the outburst follows the behavior of classical novae quite closely.

If we interpret the outbursts of T Pyx as accretion events, on the other hand, they must be of a kind resembling those of dwarf novae (i.e., ones in which matter is accreted through a disk onto a central star), rather than that invoked above for the outbursts of T CrB and RS Oph (in which the principal outburst results from the dynamical release of the infall energy of a ballistic stream). The fact that the luminosity ($M_v \gtrsim +0.8$) and colors of T Pyx at minimum do not permit the presence of a giant component, and thus demand a short orbital period (and short dynamical time scale), leads to the conclusion that its slow outburst development must be governed by the slower viscous time scale of the disk, as in dwarf novae.

It is again desirable to place T Pyx near the upper limit of the allowed distance range in an accretion model. A luminosity near the Eddington limit at maximum is again helpful in explaining the ejection of a shell, in producing the extensive mass outflow needed to produce an emission-line spectrum at that stage (dwarf novae normally have absorption-line or continuous spectra at maximum), and in understanding the occurrence of large-scale light variations near maximum, which are more rapid than the general rise and decline. (These can be attributed to density fluctuations in the outflowing wind producing rapid variations in the effective photospheric radius, just as in the thermonuclear runaway model.)

The intrinsic colors of T Pyx at maximum are in fact very close to those of an optically thick extended accretion disk. However, *their evolution during the rise to maximum is markedly different from that of the accretion events powering dwarf nova outbursts.* In the latter systems, the broad-band colors normally become *bluer* during the approach to maximum (see, for example, Grant and Abt 1959; Zuckerman 1962). The behavior

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[4] Williams (1983) measured an Hβ equivalent width of 9.7 Å for T Pyx at minimum. From Patterson's (1984) empirical correlation of this quantity with absolute magnitude, one derives a value $M_v = +5.2$. However, EW (Hβ) and M_v are only very weakly correlated when Hβ is this weak, and William's observation includes an unknown contamination from the circumstellar shell.

of T Pyx would appear to demand an outburst originating in the *inner* disk, and propagating outward, in contrast to the development in dwarf novae (see, e.g., Hassall *et al.* 1983; Schwarzenberg-Czerny *et al.* 1985; Hassall, Pringle, and Verbunt 1985). This can happen only if the outbursts result from a disk instability, and requires the storage of $\gtrsim 10^{27}$ g in the disk to reproduce the outburst energies. This far exceeds the critical mass needed to trigger dwarf nova outbursts by this instability and would imply that T Pyx must be a system of much longer orbital period.

The time scales characterizing the rise and decline of T Pyx are also problematic for an accretion model. In a dwarf nova, the rise to maximum is typically very rapid, spanning only a very few orbital cycles (Szkody and Mattei 1984). This rapid rise is in fact predicted by both models in which the mass-transfer rate from the companion star is modulated (e.g., Bath and Pringle 1981, 1982) and those in which outbursts result from instabilities in the accretion disks themselves (Meyer and Meyer-Hofmeister 1983; Faulkner, Lin, and Papaloizou 1983; Cannizzo and Wheeler 1984; Smak 1984; Mineshige and Osaki 1983). Similarly, the rates of decline of dwarf novae are observed to be highly correlated with the binary orbital periods (Bailey 1975*b*; Szkody and Mattei 1984). Application of the quantitative correlations obtained by Szkody and Mattei to the durations of outburst and decline would lead us to expect an orbital period of order $P \approx 6^{\mathrm{d}}$–20^{d} if the outbursts of T Pyx are indeed accretion events. Any lobe-filling giant in such a binary will have $M_v \lesssim +3$, that is, a visual luminosity comparable with that of the entire system at minimum. Yet, as noted above, no spectroscopic or photometric evidence of the companion star is seen.

Quiescence.—In the thermonuclear runaway model, as discussed in § II, an accretion rate $\dot{M} \gtrsim 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$ onto a massive white dwarf is needed in quiescence to fuel outbursts as frequently as every ~20 yr. This limit in turn implies a lower limit to the accretion disk luminosity: From equation (10) we deduce $M_v(\mathrm{disk}) \lesssim +3.6$ for a Chandrasekhar-mass white dwarf ($M_{\mathrm{wd}} = 1.4\ M_\odot$) seen at random orbital inclination. (Note that the root mean square emission-line widths found by Williams [1983] are intermediate between those of BT Mon, an eclipsing old nova, and those of V603 Aql, which is seen nearly pole-on.) This lower limit to the disk luminosity is indeed fainter than the absolute magnitude of T Pyx at minimum for all but the smallest allowed distances to the system. The colors of T Pyx at minimum (which are unlikely to be badly distorted by emission features—see Williams [1983]) are extremely blue, however, as noted above—much bluer in fact than an extended accretion disk.

There are at least two possible explanations, consistent with the thermonuclear runaway model, for the unusually blue colors of T Pyx at minimum. (1) If the binary is sufficiently compact, and the mass-transfer rate is sufficiently high, the temperature of the outer edge of the accretion disk could be so hot that only the Rayleigh-Jeans tail of the disk luminosity is visible optically. In this case, equation (10) overestimates the visual brightness of the disk. This explanation would be feasible if the mass-transfer rate were as high as $\sim 5 \times 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$, but only if the binary is an ultrashort period system ($P_{\mathrm{orb}} \lesssim 2^{\mathrm{h}}$). (2) It is possible that we see optically the Rayleigh-Jeans tail of the flux from a bloated white dwarf plus reprocessed radiation from the secondary. A good example of this phenomenon is MT Serpentis, the close binary nucleus of Abell 41, which also has extremely blue intrinsic colors (Grauer and Bond 1983; Green, Liebert, and Wesemael 1984). In T Pyx, we require the white dwarf to have a bolometric luminosity, at minimum, of order $3 \times 10^3\ L_\odot$, so that the heated hemisphere of the companion is also so hot that we see only the Rayleigh-Jeans tail of its flux distribution. We then see optically less than 1% of the energy radiated by the system at minimum. Even allowing for the fact that the optical energy output in a typical nova outburst amounts to only ~3% of the energy budget (most of the energy going into unbinding the ejected envelope), this hypothesis would require the energy released in quiescence to be of the same order as that expended in outburst. We must therefore further postulate that nuclear burning continues in T Pyx even in its quiescent state. Such a postulate is consistent with the slow outburst development in T Pyx (see above), which implies that the accreted envelope was only very weakly degenerate at the onset of the thermonuclear runaway. Note that if this explanation is correct, T Pyx probably shows a significant orbital modulation to its light curve, due to the strong, asymmetric heating of the secondary by the luminous primary (the "reflection effect" as in MT Ser). Its observed rapid variability (Landolt 1977*a*) implies, in any case, that accretion is ongoing.

Accretion models for outbursts generally imply that there is little or no accretion between outbursts. This poses a problem in the case of T Pyx, because the light at minimum appears to come from either a compact accretion disk itself, or a very hot blackbody. If it arises from a disk, the accretion rate deduced from the absolute magnitude (see above) is typical of old novae and UX UMa stars, objects which remain continuously in a high accretion state, and which disk instability models of dwarf novae indicate should be stable. If it arises from a hot blackbody, the bolometric correction to the luminosity in quiescence can scarcely be less than a factor of 10, in which case T Pyx radiates as much or more energy between outbursts as it does within an outburst. It is difficult (though not impossible) to meet this requirement from thermal relaxation within the accreting star, without appealing to nuclear burning, or to a sustained high accretion rate.

Nebular shell.—The nebular shell surrounding T Pyx is reminiscent of a classical nova system or planetary nebula. It is excited by an underlying UV source, whose energetic requirements are easily fulfilled by any reasonable extrapolation of the optical continuum. A lower limit to the shell mass may be obtained by estimating the mass of neutral hydrogen needed to produce the observed Hβ flux (Williams 1982) from a geometrically thin shell (angular radius 5″) which is optically thin to ionizing radiation (case A recombination). We assume a blackbody source of ionizing photons and calculate the number of neutral hydrogen absorbers needed to produce a net photoionization rate equal to the recombination rate deduced from the nebular flux. This limit is well-approximated for T Pyx by the expression

$$\log\left(\frac{M_{\mathrm{shell}}}{M_\odot}\right) \geq \log\left(\frac{M_{\mathrm{H\,I}}}{M_\odot}\right) = -8.56 + \frac{62100}{T} + 2\log\left(\frac{D}{\mathrm{kpc}}\right), \tag{11}$$

where D is the distance to T Pyx, and T is the effective temperature of the UV source, which is assumed to be responsible for the optical continuum of the central star. From the strength of He II λ4686, we may infer that $T > 50{,}000$ K. Even in the most unfavorable case (minimum T, maximum D) the deduced limit to the shell mass is ($M_{\mathrm{shell}} \geq 10^{-6}\ M_\odot$) consistent with the low envelope masses required by thermonuclear runaway models to produce rapidly recurring outbursts, particularly so if we are seeing nebular emission from the ejecta of several events.

The similarity of the spectrum to those of planetary nebulae suggests an abundance ratio CNO/(H + He) compatible with solar abundances, with nitrogen perhaps somewhat enriched relative to carbon and oxygen, and helium possibly deficient relative to hydrogen (Williams 1982). The apparent normality of the shell composition is at first sight somewhat surprising in the context of thermonuclear runaway models. All classical novae for which reasonable abundance data are available show enrichment in either heavy elements or in helium, presumably the result of dredge-up of white-dwarf matter (see Truran and Livio [1986] for a discussion). However, if the thermonuclear runaway model is to be applicable to recurrent novae, the white-dwarf masses and accretion rates must both exceed those prevailing in classical novae. In these circumstances, current theories of the dredge-up process suggest that mixing may be much less efficient. Diffusion (if operative at all; see Livio and Truran [1986]) is too slow to compete with the short recurrence time scales required; in effect, diffusion-induced convection (Prialnik, and Kovetz 1984) is excluded as a mixing process. Similarly, MacDonald's (1984) results would imply that shear-induced mixing (Kippenhahn and Thomas 1978; MacDonald 1983) may be much less efficient in this extreme. In view of the relatively poor understanding of shear mixing at present, we can only assume that the apparent lack of CNO or helium enhancements in the shell of T Pyx does not exclude a thermonuclear runaway model for its outbursts.

Of course, the normal composition of the nebular shell poses no difficulty to the accretion outburst hypothesis. Such shells are not seen in dwarf novae, however, and again point to T Pyx being a much more luminous object in outburst.

Summary.—While better knowledge of the orbital parameters and distance of T Pyx would be of great help in understanding this object, it nevertheless appears that the thermonuclear runaway model can be reconciled with all of the major features of the system. An accretion model, on the other hand, encounters major difficulties in explaining (1) the evolution of outbursts from blue to red, which implies an outward propagation of the outburst through the accretion disk, and a concomitantly high disk mass; (2) the very slow development of its outbursts, despite every evidence that it is a short-period binary system; and (3) the dominance of a hot continuum source at minimum. We therefore conclude that the outbursts of T Pyx are indeed almost certainly nuclear powered.

d) U Scorpii

$(\alpha_{1950} = 16^{\rm h}19^{\rm m}7^{\rm s}.488, \delta_{1950} = -17^\circ45'42''.89)$

U Scorpii (= BD −17°4554) is a rather exotic member of the class of recurrent novae which has undergone recorded outbursts in 1863, 1906, 1936, and 1979, with a mean interval between outbursts of $\bar{\tau}_{\rm rec} = 39$ yr, and magnitude at maximum $(m_v)_{\rm max} = 8.7$ (Barlow *et al.* 1981). It is distinguished by its extremely rapid rise to and decline from maximum; indeed, its rate of decline of 0.67 mag per day (Duerbeck 1981; Payne-Gaposchkin 1957) makes it the fastest nova discussed by Payne-Gaposchkin (1957). Unfortunately, the extremely rapid development of the visual light curve, together with the fact that the system is very faint at minimum ($V = 17.9$; see below), ensured that little was known about U Sco prior to its recent outburst. Extensive observational studies of the 1979 outburst have now provided a somewhat more secure basis upon which to build realistic theoretical models.

Spectroscopically, U Sco shows very high ejection velocities, ~ 7500 km s^{-1}, as inferred from the width of semiforbidden lines (N III λ1750; Williams *et al.* 1981). Barlow *et al.* (1981) also find Balmer emission with a full-width at zero intensity of $\sim 10{,}000$ km s^{-1} in their earliest spectrum, 8 days after maximum. Optical and ultraviolet observations of the 1979 outburst (Barlow *et al.* 1981; Williams *et al.* 1981) also allow estimates of the abundance patterns. Analyses of the emission lines have shown the nova ejecta to be depleted in hydrogen relative to helium (He/H ~ 2 by number) and possibly somewhat enriched in nitrogen relative to carbon and oxygen, although the CNO/(H + He) ratio is probably essentially solar (depending upon the assumed electron temperature). The strongest emission features at minimum are also attributable to He II (see below). Williams *et al.* (1981) estimate the mass of the ejected shell at $M_{\rm shell} \sim 10^{-7}\ M_\odot$.

Critical system parameters.—The reddening to U Sco has been directly estimated by Barlow *et al.* (1981). From the ratio of He II λ1640 to λ4686 in outburst, they find $E(B-V) \approx 0.2$; similarly, Hα/Hβ in outburst gives $E(B-V) \approx 0.35$ (on the assumption of case B recombination). Both estimates are consistent with the total reddening through the galactic plane in the direction of U Sco ($l = 357.67$, $b = +21.88$), $E(B-V) = 0.24$ (Burstein and Heiles 1982), which we henceforth adopt.

The distance to U Sco is not well-constrained. Rate-of-decline arguments place it at an exceedingly large distance, variously estimated in the range 13.6 kpc $< D <$ 95 kpc (Webbink 1978; Shylaja and Prabhu 1979; Duerbeck 1981). Given that U Sco is a galactic object, these estimates are almost certainly excessive. Nevertheless, the extremely dynamical character of outburst (high ejection velocities and rapid light-curve development) clearly points to a significantly super-Eddington event. If the bolometric correction at maximum is negligible, this in itself mandates a distance $D \gtrsim 10$ kpc. For our adopted reddening, the integrated optical energy of outburst is $E_v = 9.5 \times 10^{43}(D/10\ {\rm kpc})^2$ ergs.

The magnitude of U Sco at minimum has been estimated from spectrophotometry by Williams *et al.* (1981) and by Hanes (1985). The mean of their values (one preoutburst, and two postoutburst) gives $V_{\rm min} = 17.92 \pm 0.12$. This is somewhat brighter than preoutburst estimates ($m_{\rm pg} \approx 19.3 \pm 0.5$) by Webbink (1978) and by Barlow *et al.* (1981), but those estimates referred exclusively to blue-sensitive photographs. From the narrow-slit fluxed spectrum published by Hanes, we estimate the colors of U Sco at minimum to be $B-V \approx +0.71$, $U-B \approx -0.66$. The optical energy radiated between outbursts is then $E_v = 5.0 \times 10^{43}(D/10\ {\rm kpc})^2$ ergs, i.e., about one-half that radiated in outburst.

Hanes (1985) was able to identify absorption features (Ca H & K, Mg *b*) of a companion star (to which he assigned a spectral class G0 ± 5) in his spectrum of U Sco at minimum and to show that this identification is consistent with the *JHK* colors at minimum. Emission lines of He II λλ4420, 4542, 4686, 5412, and 6563 are also present (see also Williams *et al.* 1981). The contribution of Hα to the λ6563 line is uncertain, since none of the higher members of the Balmer series is clearly present in quiescence, whereas the next higher member of the helium Brackett series (Brγ λ5412) is definitely present. The near-ultraviolet part of the quiescent spectrum is heavily veiled by an additional blue continuum upon which appears an absorption edge corresponding approximately to the Balmer limit. Alternatively, this edge could be attributed to the λ3680 edge of neutral helium, but the model atmospheres of Wesemael (1981) indicate that, at best, this feature scarcely approaches half the strength (~20% drop in continuum level) seen in U Sco.

We have attempted to decompose the dereddened flux distribution of U Sco at minimum into contributions from the hot component and its cool companion. If we assume that the hot continuum arises from an accretion disk, we find that the disk contributes ~35% of the light of the system in the V bandpass, and that the cool component is of middle-to-late G spectral type (K0 V to G3 III to G2 I, depending on its luminosity class). For an assumed hot stellar companion, the hot star contributes ~15% of the light at V, and the spectral type of the companion is again middle-to-late G (G8 V to G3 III to G1 I). However, in this latter case, any stellar atmosphere capable of producing the pronounced absorption edge noted above (whether due to the hydrogen Balmer continuum or to the neutral helium λ3680 edge) is too cool to account for the very strong He II λ4686 emission seen at minimum. We must conclude that the source of blue optical continuum is not coincident with that of the ionizing photons, and we are therefore almost certainly seeing an accretion disk.

The full-width at zero intensity of the He II λ4686 emission line in quiescence is 2560 ± 320 km s^{-1} (Hanes 1985). If this represents Keplerian motion in the accretion disk, then the accreting object must be a white dwarf, as this value significantly exceeds twice the circular velocity at the surface of any main-sequence star. It is, nevertheless, quite a small total velocity width if the white dwarf is of average mass (or higher), implying that we must see the U Sco binary system nearly pole-on.

As for the cool component, we note that the Fe I complex at λλ3850–3890 is clearly visible in Hanes's (1985) quiescent spectrum. Its strength relative to Ca H and K suggests a spectral type not earlier than ~G3, for normal metallicity (cf. Jacoby, Hunter, and Christian 1984). The distance to U Sco cannot be much less than ~5 kpc if we are to understand the dynamical character of its outburst, nor much more than ~25 kpc if it is plausibly to be a member of the Galaxy. This implies that the absolute magnitude of the cool component lies in the range $+4 \gtrsim M_v \gtrsim 0$. In light of our fits to the flux distribution above, we thus assign to it a spectral classification G3–6 III–IV. With these estimates in hand, let us turn now to a discussion of possible outburst models.

Outburst behavior.—In a thermonuclear runaway model for U Sco, the short recurrence time scale and extremely fast nova outburst signature argue for a massive white dwarf receiving matter at a very high accretion rate. Indeed, Starrfield, Sparks, and Truran (1985) succeeded in modeling the outburst (recurrence) time scale and essential features of the light curve of U Sco with a 1.38 $M_\odot$ white dwarf accreting mass at a rate of 1.7×10^{-8} $M_\odot$ yr^{-1}. It is important to note that this model required no enrichment of CNO nuclei to fit the observed rapid light curve development, in contrast with nova models under less extreme conditions (see, for example, Starrfield, Truran, and Sparks 1978). As noted above, outburst observations indeed indicate a normal CNO abundance. We do not expect the outburst time scale to be materially altered by the high observed helium content of the ejecta: In the hot, rapidly accumulating envelope of the white dwarf, conditions leading to runaway are governed by CN-cycle burning. The roughly sevenfold reduction in hydrogen mass fraction can be compensated by a ~10% increase in temperature at the base of the accreted envelope, requiring a comparable small percentage increase in accreted mass (or recurrence time scale). However, the hydrogen mass fraction implied by observations ($X \approx 0.1$) may be too low to produce enough specific energy to cause mass ejection (Truran *et al.* 1986).

The thermonuclear model is not without its problems, however. One of these is the tendency for thermonuclear models to continue to burn, at constant bolometric luminosity, long after optical decline, which is due to a rapid increase in bolometric correction as the photosphere of the burning star retreats to white dwarf dimensions. In U Sco, however, there is a limit to how much radiation from the hot star can be hidden in the ultraviolet. The cool component of this system dominates its light at minimum; as noted above in the case of T CrB, heating effects become prominent if the ratio of hot to cool star luminosities becomes large ($L_h/L_c \gtrsim 100$; see Webbink, Rappaport, and Savonije 1983). The decay of near-ultraviolet light in tandem with the optical light curve (Barlow *et al.* 1981; Williams *et al.* 1981), and the lack of a significant difference in apparent magnitude between preoutburst and postoutburst states (Barlow *et al.* 1981; Hanes 1985) thus strongly indicate that the bolometric light curve could not have lagged much behind the optical light curve in decline. The problems of what causes the bolometric decline in thermonuclear events is not specific to U Sco, however, but appears endemic among classical novae and is related to a general inability of numerical models to reproduce the extent of continuous mass loss observed in those objects (see MacDonald, Fujimoto, and Truran 1985 for a discussion). We do not therefore regard this as a serious objection to applying a thermonuclear runaway model to the outbursts of U Sco.

A second concern is that of the origin of the very high helium abundance, ($Y \approx 0.9$), and concomitant hydrogen deficiency ($X \approx 0.1$) of the ejecta of U Sco. This composition is exceptional among classical novae, even though it is common for them to show some degree of helium enhancement (see Table 1 in Truran and Livio 1986). It most certainly was not produced by burning in the outburst, the energetics of which are dominated by the binding energy and terminal kinetic energy of the ejected envelope. Even for a 1.38 $M_\odot$ white dwarf ejecting matter with a terminal velocity of 7500 km s^{-1}, one requires only 1.2×10^{18} ergs per gram of ejected material, equivalent to converting only ~20% of its mass from hydrogen to helium. The enhancement also seems very unlikely to have originated in the donor star. Although there is no compelling observational argument with which to refute this hypothesis, the theoretical difficulties it poses are considerable. In binary evolutionary calculations in which the donor star has developed a degenerate helium core (as would be appropriate for a low-mass donor in U Sco), mass transfer invariably ceases before the mass transfer has reached the outer portions of the hydrogen-burning shell. Surface hydrogen depletions typically amount to less than ~20% of the original hydrogen mass fractions. Hydrogen depletions as large as those needed here are encountered among cool mass transfer models only in relatively massive stars caught just before core helium ignition, or in shell–helium-burning stars (case "BB" mass transfer—see Law and Ritter 1983), all of which are much too luminous to be viable models for the cool component of U Sco (see, for example, Iben and Tutukov 1985). We conclude that this enhancement is probably due to mixing in the envelope of the accreting star but with the acknowledgement on our part that it is still difficult to understand the dominance of the helium emission-line spectrum at minimum in these terms.

The argument just stated is in fact a much more damaging one for accretion models of the outburst, which can only attribute the anomalous composition to the donor star. Models of this type encounter other difficulties as well. The 1979 March pre-outburst spectrum obtained by Hanes (Barlow *et al.* 1981; Hanes 1985) reveals the same veiling blue continuum noted in postoutburst spectra, indicating that *a hot accretion disk has been present throughout.* Disk instability models can thus be excluded because the presence at minimum of a strong blue continuum with a Balmer jump in absorption indicates that the disk must lie on the stable, high-temperature branch of the effective temperatures versus surface density curve (unlike disks in dwarf novae, which apparently lie on the lower, cool branch in quiescence). A stream collision model of the type involved for T CrB and RS Oph can probably be excluded on these grounds as well, since the dissipation of the stream kinetic energy on a dynamical time scale would demand that the disk have a mass comparable with that of the stream ($\gtrsim 10^{-6}$ $M_\odot$); the white dwarf accretor is in any case too small to prevent disk formation in this scenario, and we should expect the outburst energetics to be dominated by the subsequent viscous evolution of the disk. Except for the aforementioned difficulty accounting for the anomalous composition of the ejecta of U Sco, the possibility remains of an outburst caused by the viscous decay of a parcel of mass suddenly injected into the disk by the companion G star. However, we know of no other close binary of any type in which such bursts of mass transfer occur *superposed upon* an already high background mass-transfer rate.

Quiescence.—As we have just seen, the presence of a bright accretion disk in U Sco at minimum poses severe difficulties for accretion-powered outburst models. We will now see that the properties of this disk fit a self-consistent evolutionary model of the system in which the outbursts result from thermonuclear runaways on a massive accreting white dwarf.

The presence of a G3–6 III–IV companion in the U Sco system suggests that the simplified model of mass transfer driven by nuclear evolution of a low-mass red giant, outlined by Webbink, Rappaport, and Savonije (1983), may be applicable. For these purposes, we assume, following the models of Starrfield, Sparks, and Truran (1985), that the accreting star is a 1.38 $M_\odot$ white dwarf (radius 1.9×10^8 cm). The half-width at zero intensity of the He II λ4686 line in quiescence (Hanes 1985) then implies an orbital inclination $i = 7°$. The colors of the companion star derived from our deconvolution of the flux distribution at minimum correspond to a bolometric correction B.C. $= -0.19$ (Straižys and Kuriliene 1981). This star is brighter than the accretion disk by an amount $\Delta V = +0.65$.

The results of combining equation (10), above, with equations (22), (24), and (25) from Webbink, Rappaport, and Savonije (1983), are illustrated in Figure 2. The luminosity of the donor star and mass-transfer rate are of course fixed directly by the assumed distance. The solutions for the mass of the companion star and for the orbital period demonstrate that the deduced mass-transfer rates are consistent with those driven by nuclear evolution of the cool component throughout the allowed range of possible distances to U Sco, and yield physically reasonable mass estimates for the donor star. The deduced effective temperatures for that star are in good qualitative agreement with its observationally inferred colors, though they tend to be slightly cooler (by the equivalent of from 3 spectral subclasses, for a metal-poor, Population II composition, to as much as one full spectral class, for a metal-rich, Population I composition). We note in particular that the accretion rate used by Starrfield, Sparks, and Truran in successfully modeling the recurrence time scale ($\dot{M} = 1.7 \times 10^{-8}$ $M_\odot$ yr^{-1}) falls within the allowed range and implies a distance $D \approx 14.6$ kpc to U Sco, a companion mass $M_2 \approx 0.9$–1.0 $M_\odot$, and an orbital period $P_{\rm orb} \approx 5^{\rm d}$–$9^{\rm d}$ (depending on the composition of the giant). At this distance, U Sco would lie 5.4 kpc out of the galactic plane and therefore belong to the halo population.

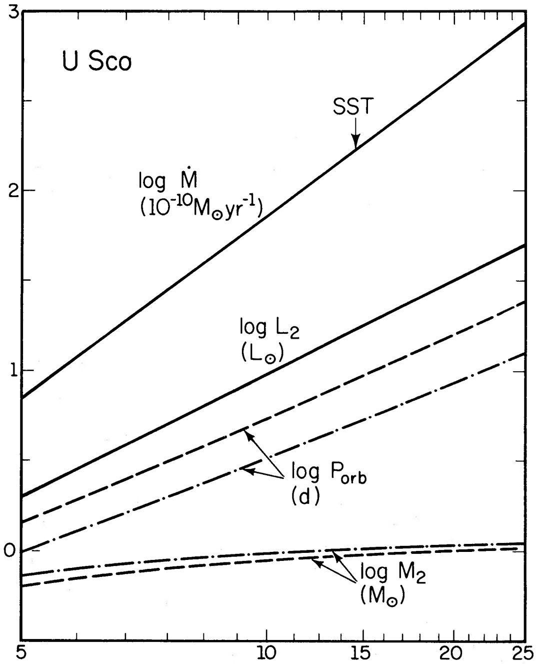

FIG. 2.—Theoretical model fits to the observed properties of U Sco, as a function of assumed distance to the system. Illustrated are the accretion rate, $\dot{M}$, the bolometric luminosity of the donor star, L_2, the mass of the donor star, M_2, and the orbital period of the binary, $P_{\rm orb}$. The duplicate curves for M_2 and $P_{\rm orb}$ correspond to different assumptions regarding the composition of the donor star: Population I ($Z = 0.02$)—*dashed lines*; Population II ($Z = 0.001$)—*dash-dotted lines*. The arrow labeled SST marks the accretion rate modeled by Starrfield, Sparks, and Truran (1985).

Summary.—We have found that the observed properties of U Sco at minimum indicate the presence of a white dwarf surrounded by a hot accretion disk, with a G3–6 III–IV companion star. These properties are consistent with an evolutionary model of the system which effects mass transfer at just the rate needed to produce thermonuclear outbursts at their observed rate of recurrence. Thermonuclear runaways in these circumstances have been previously shown to reproduce the gross outburst characteristics of U Sco (Starrfield, Sparks, and Truran 1985). Accretion models of the outburst, on the other hand, provide no plausible explanation for the abundance peculiarities in the ejecta of U Sco, nor do they easily accommodate a hot accretion disk in the quiescent state. We conclude that U Sco is almost certainly a recurrent thermonuclear nova.

e) V1017 Sagittarii

$$(\alpha_{1950} = 18^{\rm h}28^{\rm m}53\overset{\rm s}{.}44,\ \delta_{1950} = -29^\circ25'25\overset{''}{.}7)$$

V1017 Sgr (=Nova Sgr No. 5) was discovered in 1919 on Harvard plates near $m_{\rm pg} = 7$ by Ida Woods (Bailey 1919*b*),

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who also found photographic records of an earlier, lesser brightening in 1901. A photographic light curve, reconstructed from Harvard patrol plates, and covering the interval 1891 to 1937 including these two outbursts, was published by McLaughlin (1946). In 1973 February, a third outburst was discovered by Albert Jones of Nelson, New Zealand, and was widely observed. The light curves of all three outbursts are illustrated in Figure 3. A further search of 50 Harvard plates between 1937 and 1948, and of more than 600 Nantucket plates between 1956 and 1977, revealed no evidence of any other outbursts (Hoffleit 1975, 1977). Since 1954, V1017 Sgr has been monitored continuously by the Variable Star Section of the Royal Astronomical Society of New Zealand.

Spectra of V1017 Sgr at minimum have been described by Humason (1938) and by Kraft (1964). (A spectrum obtained in 1927, and identified as possibly that of V1017 Sgr by Brück [1935], is probably that of the nearby star CoD $-29°15053$.) Humason found a featureless spectrum with a strong blue continuum. In contrast, Kraft (1964) found (on a spectrogram obtained by Greenstein) a well-developed absorption spectrum of a late-type star, with superposed wide emission of Hβ, Hγ, Hδ, and He II λ4686 barely present. From three of his own spectrograms, on which the emission lines were almost absent, he classified the star as G5 IIIp (with Ca I λ4226 and Fe I λ4383 giving a later spectral type than that derived from the G band). The spectroscopic characteristics of V1017 Sgr, as well as its erratic outburst behavior, prompted its reclassification in the *Second Supplement of the Third Edition of the General Catalogue of Variable Stars* (Kukarkin *et al.* 1974) as a variable of Z And (symbiotic) type.

Photoelectric photometry at minimum has been obtained by a number of optical (Mumford 1971; Walker and Marino 1972; Landolt 1975, 1977*b*; Walker 1977; Walker, Marino, and Herdman 1977) and infrared (Feast and Glass 1974; Kenyon 1983) observers. Mumford (1971) and Walker (1977) found this object to be rapidly variable in blue light, by ~0.2

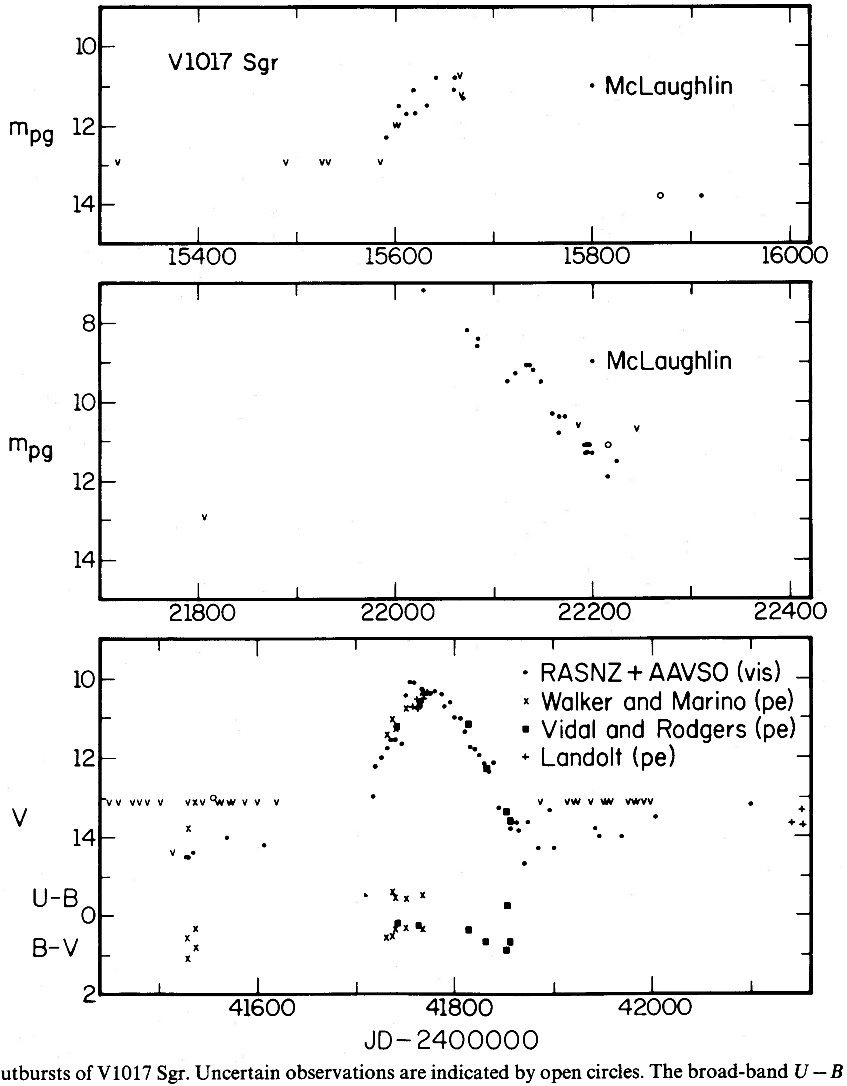

FIG. 3.—The three recorded outbursts of V1017 Sgr. Uncertain observations are indicated by open circles. The broad-band $U-B$ and $B-V$ colors, at the bottom of the bottom panel, parallel each other in their evolution through the 1973 outburst. Observations for the first two outbursts were published by McLaughlin (1946), those for the third by Bateson (1973, including the photometry by Walker and Marino), Vidal and Rodgers (1974), and Landolt (1975), with unpublished visual estimates of the RASNZ and AAVSO kindly supplied by Bateson (1977) and Mattei (1976*b*). Unpublished preoutburst photoelectric photometry by Walker and Marino (1972) was also provided by Bateson (1977).

mag, in much less than 1 hr. There is considerable dispersion in the optical magnitudes and colors, whose variations appear largely uncorrelated; excluding the discordant measures of Walker, Marino, and Herdman, we obtain for the mean $V = 13.59 \pm 0.07$ (s.e. of the mean; $n = 14$ measures), $B-V = +1.03 \pm 0.04$ ($n = 10$), $U-B = +0.31 \pm 0.11$ ($n = 10$), $V-R = +1.10 \pm 12$ ($n = 4$), $R-I = +0.82 \pm 0.07$ ($n = 4$). The single infrared observation by Feast and Glass (1974), $K = 10.58 \pm 0.29$, is in good agreement with a single observation by Kenyon (1983): $K = 10.57$, $H-K = +0.11$, $J-K = +0.60$, for which we estimate observational uncertainties of ± 0.20 mag, in each bandpass.

The reddening to V1017 Sgr, derived from the *VRIJK* photometry, the intrinsic colors of a G5 III star (Johnson 1966), and the extinction curve of Rieke and Lebofsky (1985) is $E(B-V) = 0.39 \pm 0.03$. For the absolute magnitude of a G5 III star, we adopt $M_v = +1.0 \pm 0.9$ (Straižys and Kuriliene 1981), which, together with the mean V magnitude at minimum, gives a distance $D = 1.89^{+0.98}_{-0.64}$ kpc.

It is immediately clear from Figure 3 that the outbursts of 1901 and 1973 were very similar in character (the differences being attributable to differences in photometric systems), while that of 1919 was altogether more energetic, reaching a much brighter state, and declining more slowly. It is unfortunate that only a few outburst spectra exist for this object, all from the 1973 outburst (Vidal and Rodgers 1974), and none from the 1919 outburst. Nevertheless, it can be stated that the 1919 outburst conforms *photometrically* to the pattern of classical novae: our estimate of the rate of decline, 0.024 mag day^{-1}, corresponds to $M_{\rm pg}(\max) = -6.3$ (de Vaucouleurs 1978), or $m_{\rm pg}(\max) = 6.7 \pm 0.9$ for our adopted distance and reddening. The agreement between this figure and the earliest observations of the 1919 outburst ($m_{\rm pg} = 7.2$) suggests that maximum could not have been missed by much and prompts us to speculate that this outburst was indeed thermonuclear in origin.

By the same token, however, the outbursts of 1901 ($m_{\rm pg}[\max] = 10.9 \pm 0.1$) and 1973 ($V[\max] = 10.36 \pm 0.05$) reach only $M_{\rm pg}(\max) = -2.1$ and $M_v(\max) = -2.23$, respectively, much too faint to be plausible thermonuclear events. We conclude that these must be (disk) accretion events. This conclusion is supported by the spectroscopic development of the 1973 outburst (Vidal and Rodgers 1974), which shows a strong continuum throughout, and relatively low excitation: He II λ4686 is by far the highest excitation feature seen. The absence of [O III] λ5007 emission indicates that the continuum source is dense (and probably optically thick) and not recombination continuum from an optically thin shell as suggested by Vidal and Rodgers. The *BVRI* colors at maximum ($B-V = +0.31 \pm 0.05$; $V-R = +0.45 \pm 0.04$; $R-I = +0.30 \pm 0.02$: Vidal and Rodgers 1974; Landolt 1975) are roughly consistent with those of a reddened accretion disk. Integration of equation (10) throughout the course of the outburst would then yield, for the total mass accreted in the event,

$$\Delta M \approx 6.9 \times 10^{-6}\, M_\odot (M_{\rm wd}/M_\odot)^{-1} (D/1.89 \text{ kpc})^3 (2 \cos i)^{-3/2} ,$$

where $M_{\rm wd}$ is the mass of the (presumed) white-dwarf accretor, D the distance to V1017 Sgr, and i its orbital inclination. Thus, if the 1919 outburst was indeed a thermonuclear runaway, accretion events such as those in 1901 and 1973 probably deposit a significant fraction of the ignition mass within one event; the recurrence frequency of accretion events ($\sim$0.014 yr^{-1}?) probably then exceeds that of thermonuclear events by no more than an order of magnitude, or so.

Although it does not strictly satisfy the first of the two criteria we set for recurrent novae, V1017 Sgr nevertheless presents the intriguing possibility of being a hybrid object, showing both thermonuclear and accretion events. Very few such systems are now known, the most famous being the old nova GK Persei, which now displays dwarf-nova–like outbursts (Mattei 1976*a*). V1017 Sgr is not prohibitively faint, and with a G5 IIIp companion should be a promising candidate for a spectroscopic orbit determination. A normal giant of this spectral type may be expected to fill its Roche lobe for an orbital period in the range $2^{\rm d}$–$20^{\rm d}$.

f) *WZ Sagittae*

($\alpha_{1950} = 20^{\rm h}05^{\rm m}20^{\rm s}.65$, $\delta_{1950} = +17^\circ 33' 30''.1$)

Although long classified as a recurrent nova, WZ Sge was found, soon after its discovery by Mackie (Bailey 1919*a*), to possess a high proper motion (van Maanen 1926, 1928, 1934), and was therefore identified as an anomalously faint nova. Of its three known outbursts (in 1913, 1946, and 1978), the last was by far the best-observed. This system is now widely recognized as an extreme example of a dwarf nova, whose rare outbursts possess all of the major anomalies characterizing the supermaxima of SU Ursae Majoris–type systems (see, e.g., Patterson *et al.* 1981; Vogt 1981). We therefore reject WZ Sge from the class of recurrent novae.

g) *V616 Monocerotis*

($\alpha_{1950} = 6^{\rm h}20^{\rm m}11^{\rm s}.188$, $\delta_{1950} = -2^\circ 10' 10''.00$)

First discovered as a bright transient X-ray source (Elvis *et al.* 1975*a*, *b*), V616 Mon (=A0620−00) was soon identified optically by Boley *et al.* (1975, 1976). A search of the Harvard plate files (Liller and Eachus 1975; Eachus, Wright, and Liller 1976) revealed an earlier optical outburst, confirmed by Shugarov (1976), in 1917 November. At minimum, the spectrum of V616 Mon is that of a K4 V to K7 V star upon which is superposed an emission-line system attributed to an accretion disk (Oke 1977; Whelan *et al.* 1977); the derived distance to the system is $\sim$870 pc (Oke 1977), implying an absolute visual magnitude at maximum of only $M_v = +0.22$ for an interstellar reddening $E(B-V) = 0.40$ (Oke and Greenstein 1977). The orbital period has been established photometrically at $P = 7^{\rm h}.8$ (McClintock *et al.* 1983), and recent spectroscopy (McClintock and Remillard 1986) has revealed surprisingly large radial velocity variations in the K-star spectrum, indicative of a massive ($> 3.20\, M_\odot$) compact companion. V616 Mon is thus a black hole candidate and is, in any case, now widely recognized as the prototype for a class of soft X-ray transient sources (classification XND in the *Fourth Edition of the General Catalogue of Variable Stars* [Kholopov *et al.* 1985]). In view of its low intrinsic optical luminosity in outburst, and fundamentally different physical nature, we exclude it from our discussion of recurrent novae.

h) *VY Aquarii*

($\alpha_{1950} = 21^{\rm h}09^{\rm m}28^{\rm s}.33$, $\delta_{1950} = 09^\circ 01' 56''.3$)

This star was discovered by Ross (1925); its decline from $m_{\rm pg} = 8.4$ on 1907 August 8 to $m_{\rm pg} = 12.6$ on 1907 August 27 was recorded by the Harvard sky patrol, which revealed no other positive observations between 1890 and 1925 (Woods 1925). A second eruption (in order of discovery) was detected in 1962 (Strohmeier 1962*a*, *b*; Huth 1962), the star declining from $m_{\rm pg} = 9.75$ mag to $m_{\rm pg} = 11.20$ mag, and a third in 1973 July (McNaught 1982; Wenzel 1983). Subsequent examination of plates from 1928 to 1982 by Richter (1983*a*) led to the discovery of yet another outburst in 1958 June; he noted that the blue color near maximum light in the 1958 outburst was more reminiscent of U Gem stars than of classical novae spectra. A later examination of plates from the periods 1925–1952 and 1962–1981 (Liller 1983) revealed three additional definite outbursts, in 1929 June ($m_{\rm pg} = 8.0$), 1934 June ($m_{\rm pg} = 9.0$), and 1942 October ($m_{\rm pg} = 11.0$). Another possible outburst (one plate) was found in 1941 April ($m_{\rm pg} = 11.1$). Other apparently reliable observations of increased brightness were found by Richter (1983*b*) to have occurred in 1939 August, 1940 August, 1964 October, 1965 September, 1966 July, and 1967 October. Recent outbursts have been observed in 1983 November–December (McAdam *et al.* 1983; Medway, Morrison, and Bortle 1983; Verdenet 1984) and in 1986 May (Lubbock and McNaught 1986; Mattei and Harvan 1986; Perez and McNaught 1986; McNaught 1986), reaching $m_v = 10.3$ in each case. A part of the light curve for the 1983 outburst is given by Huruhata (1984), and it exhibits a sudden decrease on December 11, similar to those in SS Cygni–type stars.

A spectrum of VY Aqr has been obtained at minimum in 1983 July, when the star was fainter than 16th magnitude (Hendry 1983), and was found to be similar to that of a Be star or a dwarf nova. The hydrogen lines, Ca II K line and He I lines all appeared with double emission, central absorption profiles. The total widths of the emissions averaged 22.5 Å (corresponding to ~ 1600 km s^{-1}), with peak-to-peak separations of the order of 1000 km s^{-1}.

Patterson has found evidence of periodic photometric modulation at minimum suggestive of an orbital period $P \approx 0\overset{d}{.}22$ (Ritter 1984). This observation plus the extremely short occasional recurrence time of this object, of order 1 yr, and its spectroscopic appearance at minimum point clearly to its being a dwarf nova, as suggested by Ritter (1984), and not a recurrent nova. This conclusion is strengthened by the observed colors in the 1958 outburst (Richter 1983*a*). At any rate, the outbursts are almost certainly not caused by a thermonuclear runaway. The necessary accretion rate to build up a sufficiently massive envelope (even on the most massive white dwarf) is $\dot{M} \gtrsim 5.6 \times 10^{-7}\, M_\odot$ yr^{-1}, which is both implausibly high and, more importantly, would imply such a high rate of compressional heating that a thermonuclear runaway under degenerate conditions would not occur. The profiles of the emission lines, and their peak-to-peak separations (~ 1000 km s^{-1}; Hendry 1983), seem to indicate that the accretion disk is optically thin (or at least in a low state). This is also inconsistent with the high accretion rates necessary to power a thermonuclear runaway, but again entirely consistent with our assignment of VY Aqr to the class of dwarf novae.

i) RZ Leonis

($\alpha_{1950} = 11^{\rm h}34^{\rm m}48\overset{\rm s}{.}75$, $\delta_{1950} = +02°05'31\overset{''}{.}3$).

RZ Leo is identified as a recurrent nova in the *Fourth Edition of the General Catalogue of Variable Stars* (Kholopov *et al.* 1985). Very little was known about this system until its recent outburst, $m_v(\max) = 12.9$, in 1984 late December (Mattei *et al.* 1985; Cristiani, Duerbeck, and Seitter 1985; Scovil 1985; McNaught 1985). It was originally discovered by M. Wolf at magnitude $m_{\rm pg} = 10$–11 on two plates taken on 1918 March 13.4 at Königstuhl (Mündler 1919). An additional positive observation on 1918 March 12 ($m_{\rm pg} = 11.5$) was later found by Beljawsky (1923) on a plate taken at Simeïs, but, beside these positive identifications, only scattered negative observations exist from this era (Mündler 1919; Beljawsky 1923; Rügemer 1933).

Finding charts published by Herbig (1958), Brun and Petit (1957), and Vogt and Bateson (1982) show RZ Leo at $m_{\rm pg} \approx 17.5$ in quiescence, implying a relatively small amplitude of outburst (as novae go). Vogt and Bateson suggested the system might be a dwarf nova of the same type as WZ Sge ("extremely rare outburst with large amplitude"). A spectrum obtained by Cristiani, Duerbeck, and Seitter (1985) during decline from the 1984–1985 outburst supports this suggestion. Photoelectric photometry obtained by Brosch and Orio (1985) in 1985 late January revealed that RZ Leo, like WZ Sge and VY Aqr in their outbursts, had declined abruptly to minimum. We therefore concur in assigning RZ Leo to the class of dwarf novae.

j) V1195 Ophiuchi

($\alpha_{1950} = 16^{\rm h}57^{\rm m}24^{\rm s}$, $\delta_{1950} = -20°49\overset{'}{.}1$).

This object is listed by Kukarkin *et al.* (1971) as a possible recurrent nova. It was discovered by Plaut (1968*a*) in whose list of variable stars in Field 2 of the Palomar-Groningen Variable Star Survey it is cataloged as No. 71. Plaut (1968*b*) found two maxima, on 1956 June 12 and 1959 April 29, and considered it a possible recurrent nova or long-periodic variable. No other positive observations exist for this object.

The light curve of this star as derived from Plaut's observations (Fig. 4) strongly suggests that it is a dwarf nova, with a mean maximum at $m_{\rm pg} \approx 16.0$, and minimum at $m_{\rm pg} \gtrsim 20.0$. In the one well-observed outburst (Fig. 5), V1195 Oph remained visible for only 5 days. Convolved with the dates of observation, this outburst length gives an effective duration of coverage of 110 days, implying a ~ 55 day recurrence time scale, again typical of dwarf novae.

k) V529 Orionis

($\alpha_{1950} = 5^{\rm h}55^{\rm m}24^{\rm s}$, $\delta_{1950} = +20°15\overset{'}{.}2$).

The remarkably checkered history of this putative recurrent nova has been recently reviewed by Ashworth (1981), who identified Hevelius's discovery observation as having been made on 1678 March 28, rather than 1667 April 18 as heretofore assumed (Baily 1843), and who showed furthermore that its outburst of circa 1740 was fictitious. A third outburst on 1894 February 24 was reported by Shackleton (1894), but his account is extremely vague and entirely consistent with a mistaken observation of the nearby Mira-type variable, U Orionis, which would have been declining from its maximum ($m_v = 6.07$) on or about 1894 February 8 (Markwick 1898). Finally, a possible positive sighting (at $m_v = 10.7$) on 1975 January 29 by a Hungarian amateur astronomer (Brlas 1975) must be laid as well to an erroneous identification. The only extant finding chart for this star (Brun and Pettit 1957) is based on the erroneous position appearing in the *Prodromus Astronomiae* (Hevelius 1690). The correct position (Ashworth 1981) is quoted above.

There is thus only a single reliable sighting of V529 Ori. The exact nature of this object is unknown; although at $l = 188\overset{\circ}{.}94$. $b = -1\overset{\circ}{.}93$, it could be a nova, there remains no basis for believing it to have recurred. Recent attempts to recover it (Shara 1984) have thus far been fruitless.

IV. DISCUSSION

We have examined the existing observational material concerning all recurrent novae and attempted to construct theoretical models for each system. We have found this "class" of

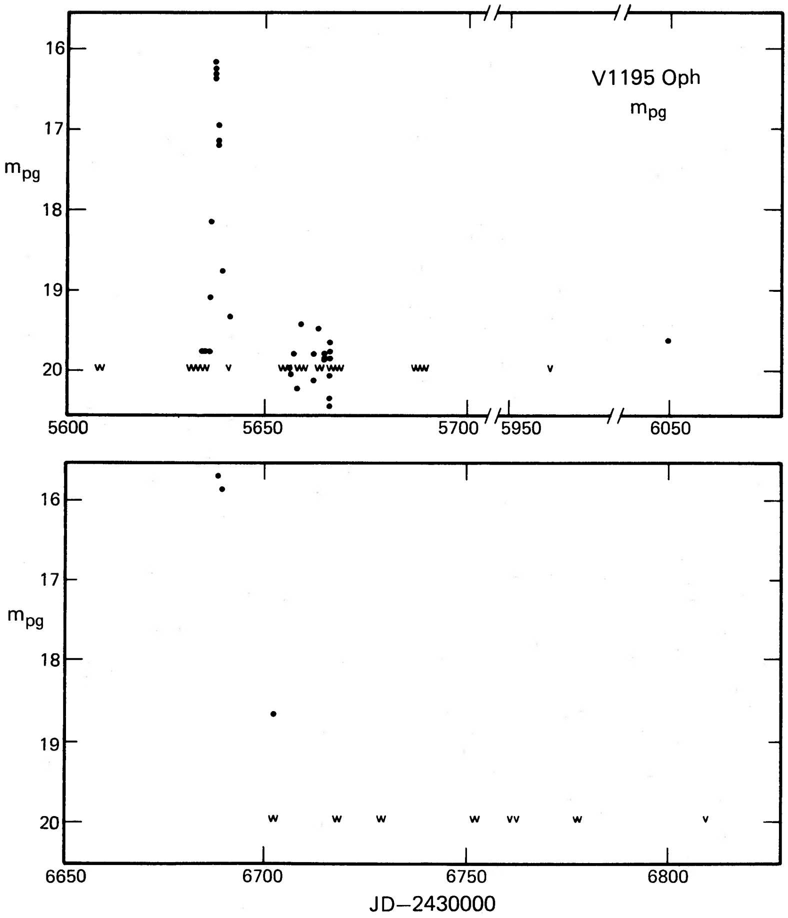

FIG. 4.—The complete light curve of V1195 Oph (Plaut 1977)

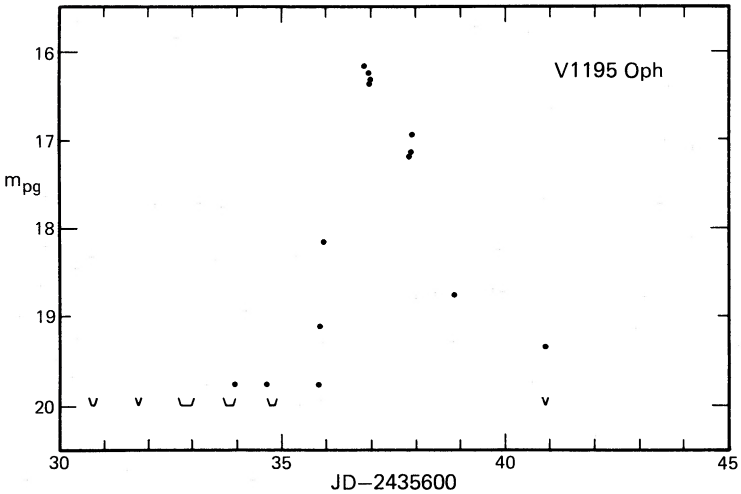

FIG. 5.—Detailed light curve of the 1956 June outburst of V1195 Oph

objects to be extremely inhomogeneous from an observational point of view, and consequently we have suggested that different models for the outburst apply to different systems.

Five objects were not dismissed as being clearly dwarf novae or X-ray transients; they are T CrB, RS Oph, U Sco, T Pyx, and V1017 Sgr. These systems can be further subdivided into two subgroups of two objects each (with one object remaining as a hybrid type). We proposed that the outbursts of U Sco and T Pyx are powered by thermonuclear runaways, while those of T CrB and RS Oph are accretion events. In what follows we shall discuss some of the properties of each of these subclasses.

a) Recurrent Novae Caused by Thermonuclear Runaways

As we have seen in § II, thermonuclear runaway models of recurrent novae require both very massive white dwarfs (close to the Chandrasekhar limit) and high accretion rates, $\dot{M} \gtrsim 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$, in order to produce short recurrence times. A question which immediately comes to mind is then: What is the cause for the considerable difference in outburst characteristics between U Sco and T Pyx, both of which we explained in terms of a thermonuclear runaway model? Observationally, it is quite clear that the outbursts of U Sco represent more violent (dynamical) events than those of T Pyx. This is exhibited both by the much more rapid development of the light curve (in particular, the rise to maximum) and by the observed ejection velocities (850–2000 km s^{-1} in T Pyx, 7500–10,000 km s^{-1} in U Sco). The luminosity at maximum light cannot serve by itself as an unambiguous tool for determining the strength of the outburst, since its value is dependent on the uncertain distance to the objects.

Since both U Sco and T Pyx appear to show more or less a solar composition of CNO elements, the difference in the strength of the eruption can most likely be attributed to a difference in the degree of degeneracy at the bottom of the accreted envelope, at the point of ignition. The level of degeneracy, in turn, is determined to a large extent by the accretion rate (which determines the rate of compressional heating) and by the white-dwarf luminosity. We do not have a very good handle on the difference in the accretion rates in the two systems, in spite of the fact that we know that the mean recurrence time for T Pyx is shorter. This difficulty stems from the fact that a small difference in the mass of the underlying white dwarf can be compensated by a correspondingly larger (relative) difference in the accretion rate, due to the extreme sensitivity of the pressure at the base of the accreted envelope to the white-dwarf mass (see § II). However, we have found strong observational evidence (in particular the unusually blue colors at minimum in T Pyx), that the white dwarf in T Pyx is considerably brighter at quiescence than the one in U Sco. It is thus very reasonable to assume that the major cause for the less degenerate environment in T Pyx is the higher white-dwarf luminosity.

This explanation fits also into the framework of our evolutionary scenario for U Sco. At a mass of 0.9–1.0 $M_\odot$, the donor star in U Sco lies only 0.1–0.2 $M_\odot$ below the critical mass above which it would be unstable to dynamical time-scale mass transfer. This system must therefore be relatively young, in terms of its present phase of mass transfer, and it is therefore possible, even likely, that little reheating of the white dwarf has yet occurred. It may thus be possible to understand the differences between U Sco and T Pyx (both powered by thermonuclear runaways) in terms of their evolutionary phases and the concomitant consequences for the accretion and runaway processes.

b) Recurrent Novae Caused by Accretion Events

The two objects belonging to this subclass are T CrB and RS Oph. The systems are very similar in orbital period, in the type of secondary star (an M giant), and in spectral evolution through the outburst. In particular, both systems show the appearance of coronal emission lines sometime following maximum light. The systems overlap considerably (in terms of their binary properties) with some symbiotics, and indeed T CrB and RS Oph are frequently included among symbiotic stars. However, they are distinguished by (i) shock-type dynamical ejection of mass at high velocities, and (ii) light curves exhibiting an extremely rapid rise followed by a smooth decline.

It is interesting that both T CrB and RS Oph lie at the short-period extreme of the range of periods spanned by symbiotic stars with well-established orbits (see the tabulation in Webbink 1986). Although accretion events are believed responsible for the outbursts of a number of other symbiotics (Bath and Pringle 1982; Kenyon *et al.* 1982; Kenyon and Webbink 1984), none shows the shock-type outbursts of these two systems. In the context of the models outlined above for T CrB and RS Oph, this difference follows largely from the longer orbital periods of the other symbiotic systems. These models invoke dynamical dissipation of the excess kinetic energy of the original ballistic stream from the donor star (the same energy source as produces the "hot spot" in dwarf novae), either by direct collision with the accreting star, or by collapse into a ring about that star. The orbit of that ballistic stream scales in proportion to the binary separation, and therefore the energy available dynamically in the inverse proportion. Moreover, the time scale on which that energy is released presumably scales with the dynamical time scale of the binary, i.e., P_{orb}. Thus we expect the luminosity of the principal maximum seen in T CrB and RS Oph to scale as $L \sim E/\tau_{\mathrm{dyn}} \sim P_{\mathrm{orb}}^{-5/3}$, all other things being equal. Furthermore, we may anticipate much denser stellar winds from lobe-filling stars in longer period orbits. This will not only inhibit coronal line formation, but the greatly reduced density contrast between the stream and ambient stellar wind also reduces the shock velocity. The short orbital periods of accretion-powered recurrent novae, in comparison with symbiotic stars, are therefore not surprising.

c) Identifying Features of Recurrent Novae

It would be useful to attempt to define some characteristics of recurrent novae which would enable observers to identify them as such, even from the observations of a single outburst.

One such property is a consequence of the fact that thermonuclear runaway models of recurrent novae require the accreting white dwarf to be close to the Chandrasekhar limit. As a result, the envelope mass at the time of the runaway is much smaller than that in typical classical novae (of order $10^{-6}\ M_\odot$, or even less, compared to $\sim 10^{-4}\ M_\odot$ for a 1 $M_\odot$ white dwarf). At optical maximum, the density of such a low-mass envelope is so low ($\lesssim 10^{-13}$ g cm^{-3}) that its electron scattering opacity, κ_{es}, can exceed the true absorption opacity, κ_{ab}, by as much as four orders of magnitude. Thus, while the nominal photosphere of the nova may be quite extended, the stellar continuum is formed deep within the envelope, where $(\tau_{\mathrm{es}}\tau_{\mathrm{ab}})^{1/2} \approx 1$. We thus expect *the spectrum of a recurrent thermonuclear nova at optical maximum to depart significantly from a blackbody, and, indeed, to appear as an emission-line object*, as indeed was observed in the case of T Pyx. The optical continuum flux distribution should remain extremely blue through maximum, rather than cooling to an A or F supergiant spectrum as typical of classical novae at optical maximum. We are unaware of any classical nova with a well-observed maximum (other than very slow novae) which fits this description.[5]

As for accretion-powered recurrent novae, the examples of T CrB and RS Oph strongly suggest shock-type ejection as the unifying feature. Indeed, if one appeals only to disk accretion, the disk luminosity is effectively limited to the Eddington luminosity (see, e.g., Meier 1982), and the time scale for the evolution of the outburst, the viscous time scale of the disk, becomes exceedingly long—of the order of the orbital period or longer (Bath and Pringle 1982). One must appeal to dynamical time scale phenomena (as discussed by Livio, Truran, and Webbink [1986]) to achieve a reasonable facsimile to a classical nova light curve. We therefore suggest that it is the appearance of features associated with this shock-type ejection—exceptionally high ejection velocities, *decreasing* with time; appearance of high-excitation coronal line emission and X-ray emission (see Mason *et al.* 1986) during decline—which distinguish recurrent novae of this class.

In this connection, we call the reader's attention to a system that shows somewhat similar features to those of T CrB and RS Oph: AS 295 B = V4074 Sgr ($\alpha_{1950} = 18^h12^m51^s.8$, $\delta_{1950} = -30°52'18''$; Herbig and Hoffleit 1975). At minimum, its light is dominated by AS 295 A, a K0 III giant at $m_{pg} = 12.3$, $3''$ distant. AS 295 B is known to have undergone a nova-like outburst in 1965 July, in which it rose on a short time scale to $m_{pg} = 8.6$. No other outbursts were found between 1900 and 1953 (on Harvard RB and AM plates) and between 1957 and 1964 (on Maria Mitchell plates). The coronal lines [Fe X] $\lambda 6374$, [Fe XI] $\lambda 7891$, [Fe XIV] $\lambda 5303$, and [Ar X] $\lambda 5533$ were observed 9 yr after the outburst. While the coronal lines in RS Oph are indeed very similar (see, e.g., Dufay *et al.* 1964), they disappeared about 200 days after the maximum. In T CrB, they disappeared only ~ 12 days after maximum (Bloch *et al.* 1946), although [Fe X] reappeared briefly during the decline from secondary maximum (Sanford 1949). The long visibility of coronal emission from AS 295 B may thus be related to its much slower outburst development (time to decline 3 mag, $t_3 \sim 120$ days, compared with $t_3 \sim 5.5$ days for T CrB, and $t_3 \sim 10$ days for RS Oph). At any event, V4074 Sgr deserves more attention in the future.

A common characteristic of recurrent novae is a relatively bright absolute magnitude at minimum. If the system contains a giant (as accretion-powered recurrent novae probably must), the luminosity of the system at quiescence has of course the luminosity of the giant as a lower limit. However, if the outburst is caused by a thermonuclear runaway (and the secondary star is not a giant), the requirements imposed on the system to produce the short recurrence times ($M_{wd} \approx M_{Ch}$, $\dot{M} \gtrsim 10^{-8}$ $M_\odot$ yr^{-1}) result in an upper limit on the absolute magnitude at minimum (due to the accretion luminosity, eq. [10]), $M_v \lesssim +3.6$, considerably brighter than in most classical nova systems. Consequently, in either outburst model *a smaller range can be expected for recurrent novae.* There is thus a physical basis for the classical amplitude-recurrence time relation for cataclysmic stars (Kukarkin and Parenago 1934).

V. SUMMARY

Our examination of the available data on known (or suggested) recurrent novae has led us to the (perhaps not surprising) conclusion that this is a very heterogeneous class of objects.

We have presented detailed models, which can account for most of the observations, suggesting that the outbursts of *U Sco and T Pyx are caused by thermonuclear runaways on the surface of massive white dwarfs.* On the other hand, *the outbursts of T CrB and RS Oph are very probably accretion events, initiated by a burst of mass transferred from a giant companion on to a main-sequence star.*

V1017 Sgr fails our criteria for classification as a recurrent nova, being more properly considered a symbiotic star, but it presents an interesting possibility. Available data are not sufficient to draw definite conclusions, but it appears that this system may be a hybrid case which exhibits both thermonuclear runaways and dwarf-nova–like eruptions, making it similar to GK Per.

We assign *V1195 Oph, RZ Leo, VY Aqr, and WZ Sge to the class of dwarf novae.* There is no reliable basis to believe that V529 Ori has recurred.

We are grateful to the many individuals who, over the course of several years, supplied unpublished material used in the course of this work: Dorrit Hoffleit, for a summary of observations of V1017 Sgr; Arlo Landolt, for unpublished observations of this system; the late Lukas Plaut, for the communication of his observations of V1195 Oph; and Michael Shara, for advising us of his unsuccessful search for V529 Ori, and for his advice regarding the apparent rate of expansion of the shell around T Pyx. Special thanks are due to Janet Mattei and Frank Bateson, for the liberal use of the observational archives of the American Association of Variable Star Observers and the Variable Star Section of the Royal Astronomical Society of New Zealand, respectively. Finally, we thank Dimitri Mihalas and James Kaler for useful discussions regarding the interpretion of spectra of U Sco and V1017 Sgr, and Jay Gallagher for calling AS 295 B to our attention. M. L. acknowledges support from the Ray and Miriam Kline Prize. This research was supported in part by National Science Foundation grants AST 83-14415 and AST 83-17916 to the University of Illinois.

APPENDIX

The luminosity per unit wavelength interval, from both sides of an optically thick accretion disk is

$$L_\lambda = 2 \int_{R_*}^{R_d} 2\pi^2 r B_\lambda(T) dr \, , \tag{A1}$$

where R_* is the radius of the accreting star, R_d is the outer disk radius, and $B_\lambda(T)$ is the Planck function. The temperature

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[5] Note that T CrB and RS Oph, both of which we conclude are accretion-powered, show strong *absorption-line* spectra at maximum (see Morgan and Deutsch [1947], and Wallerstein [1958], respectively). They must therefore have much denser photospheres at maximum than is possible for thermonuclear recurrent novae.

distribution in standard disk models is given by (e.g., Shakura and Sunyaev 1973).

$$T(r) = \left(\frac{3GM\dot{M}}{8\pi\sigma R_*}\right)^{1/4}\left(\frac{R_*}{r}\right)^{3/4}\left[1-\left(\frac{R_*}{r}\right)^{1/2}\right]^{1/4} . \tag{A2}$$

If the maximal disk temperature $T_{\max}$ and the temperature at the outer edge of the disk $T_{\rm out}$ satisfy (a condition typically satisfied in cataclysmic variables)

$$T_{\max} \gg \frac{hc}{\lambda K} \gg T_{\rm out} , \tag{A3}$$

where λ corresponds to the visual range, the limiting value of the integral in equation (A1) becomes independent of R_* and R_d, giving (Lynden-Bell 1969)

$$L_\lambda = \frac{20}{\pi^2}\,\Gamma\left(\frac{8}{3}\right)\zeta\left(\frac{8}{3}\right)\left(\frac{6}{5}\,hc^2\right)^{1/3}(GM\dot{M})^{2/3}\lambda^{-7/3} , \tag{A4}$$

where ζ is the Riemann zeta function and all other symbols have their usual meaning.

When convoluted with the filter response function V_λ (Allen 1973), equation (A4) gives for the absolute magnitude at V,

$$\bar{M}_v(\text{disk}) = -9.48 - \frac{5}{3}\log_{10}\left(\frac{M}{M_\odot}\,\frac{\dot{M}}{M_\odot\ \text{yr}^{-1}}\right) . \tag{A5}$$

If we include the dependence of the observed absolute magnitude on the inclination, i, of the disk axis to the line of sight, we obtain

$$M_v(\text{obs}) = -9.48 - \frac{5}{3}\log_{10}\left(\frac{M}{M_\odot}\,\frac{\dot{M}}{M_\odot\ \text{yr}^{-1}}\right) - \frac{5}{2}\log_{10}\,(2\cos i) . \tag{A6}$$

The convolution of equation (A4) with the response functions for the Johnson U and B filters gives

$$B-V = +0.07 \tag{A7}$$

and

$$U-B = -1.09 . \tag{A8}$$

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