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A MODEL FOR THE OUTBURSTS OF THE RECURRENT NOVA RS OPHIUCHI

MARIO LIVIO,[1] JAMES W. TRURAN, AND RONALD F. WEBBINK
Department of Astronomy, University of Illinois
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ABSTRACT

A model is presented for the outbursts of the recurrent nova RS Ophiuchi. The known observational constraints are reviewed, and difficulties with possible alternative models for these outbursts are discussed. We demonstrate, specifically, that the high accretion rate demanded to reconstitute a sufficient envelope to trigger a thermonuclear runaway on the short recurrence time scale for RS Oph implies a luminosity and effective temperature which are incompatible with observations of the system at quiescence. Our proposed model, similar to that advanced by Webbink for the outbursts of T CrB, involves an episodic accretion event and the direct impact of the accretion stream with the secondary, which is assumed to be an expanded main-sequence star. Our model is shown to be consistent both with all existing observations and with the similarities and differences of RS Oph and T CrB both in and out of outburst.

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

I. INTRODUCTION

The recurrent nova RS Oph is an interesting and particularly well studied member of the " class " of recurrent novae, which has to date eluded theoretical interpretation. It is known to have undergone outbursts in 1898, 1933, 1958, 1967, and 1985, implying a short average recurrence interval of ~ 22 yr. It is a binary system consisting of an M0 III or M2 III giant and a blue companion. It is characterized by an outburst range of approximately $\Delta m_v \approx 6.9$, typical for recurrent novae, and by an extremely rapid rate of decline from maximum; the outbursts themselves are remarkably similar from event to event. While direct information regarding the masses or relative masses of the binary components is not yet available, Garcia (1986) has recently derived a binary period of ~ 230 days for this system.

The many similarities of this system to the recurrent nova T CrB—the character of the outburst spectra, the rapid developments of the visual light curve, the very comparable binary periods, and the giant components—have strongly encouraged us to seek a similar model for the outbursts. In the next section, we first briefly review some observational factors which serve to constrain models for RS Oph. In § III, we examine possible alternative models for the outbursts, including in particular the thermonuclear runaway model and disk accretion models. Our own theoretical model for RS Oph is then elaborated and shown to be consistent with known observational constraints. Discussion and conclusions follow.

II. SOME OBSERVATIONAL CONSIDERATIONS

The energetics of the RS Oph system both in outburst and at quiescence provide essential input to theoretical modeling, as does information regarding the binary characteristics. Our assumed conditions are arrived at in the following manner.

The mean apparent magnitude of RS Oph at minimum is $\bar{V}_{\rm RS} = 11.5$, while the average peak magnitude in outburst is $\bar{V}_{\rm peak} \approx 4.6$. Szkody (1977) finds $K = 6.55$ at minimum. The spectral type for the giant inferred at minimum is M0 (Sanduleak and Stephenson 1973; Kenyon 1985, private communication) or M2 (Barbon, Mammano, and Rosino 1968). The intrinsic color of the giant component is given by Ridgway *et al.* (1980), $(V-K)_0 = 3.78$ (for M0 III) or $(V-K)_0 = 4.30$ (for M2 III), and the bolometric correction BC = 1.28 (for M0 III) or BC = 1.68 (for M2 III). Correction for reddening follows from the work of Cassatella *et al.* (1985), yielding $E_{B-V} = 0.73 \pm 0.05$, and of Rieke and Lebofsky (1985), who find $E_{V-K}/E_{B-V} = 2.744 \pm 0.024$ and $A_V/E_{B-V} = 3.09 \pm 0.03$; hence, $A_V = 2.25 \pm 0.18$. The apparent visual magnitude of the giant, uncorrected for reddening, is then $V_g = 12.33$ (for M0 III) or $V_g = 12.85$ (for M2 III), and the apparent bolometric magnitude for the giant, corrected for reddening, is $(m_{\rm bol})_0 = 8.80$ (for M0 III) or $(m_{\rm bol})_0 = 8.92$ (for M2 III).

We can then obtain an estimate for the distance to RS Oph and thus of the outburst energy as follows. For the binary system, we adopt the parameters $M_g = 3\ M_\odot$, $M_s = 2\ M_\odot$ (assumed simply on the basis of the similarity to T CrB; at this point we do not wish to imply that the possibility of having a white dwarf is excluded), and $P_{\rm orb} = 230^{\rm d}$. These imply a separation $a = 270\ R_\odot = 1.88 \times 10^{13}$ cm and $R_{g,\rm lobe} = 112\ R_\odot = 7.84 \times 10^{12}$ cm. If we further assume that the giant is filling its Roche lobe and adopt the effective temperatures for giants provided by Ridgway *et al.* (1980), $T_g = 3895$ K (for M0 III) or $T_g = 3730$ K (for M2 III), we obtain for the giant luminosity $L_g = 2600\ L_\odot$ (for M0 III) or $L_g = 2180\ L_\odot$ (for M2 III) and $M_{{\rm bol},g} = -3.78$ and $M_{v,g} = -2.50$ (for M0 III) or $M_{{\rm bol},g} = -3.59$ and $M_{v,g} = -1.91$ (for M2 III). The distance to RS Oph is then $D = 3.29$ kpc (for M0 III) or $D = 3.18$ kpc (for M2 III), and the total outburst energy is given by integrating over the visual light curve to give (with L_g as above) $E_{\rm tot} = 1.34 \times 10^{45}$ ergs (for M0 III) or $E = 1.25 \times 10^{45}$ ergs (for M2 III). This total outburst energy is certainly consistent with the value of 1.12×10^{44} ergs found for T CrB (Webbink 1976) and the fact that the outburst in RS Oph is of a longer duration.

Our subsequent discussions are built upon our use of these parameters for RS Oph. We note that the distance estimate can be

[1] On leave from Department of Physics, Technion, Israel Institute of Technology, Haifa.

reduced (say to ~ 2.5 kpc) if one assumes the giant to underfill its Roche lobe or assumes a smaller total mass (by a factor of ~ 2), but this would not significantly alter our estimates of the energetics and thereby does not strongly influence our conclusions. In particular, the qualitative picture we are going to present will not be altered even if the distance is reduced to 1.6 kpc, the preferred value based on 21 cm radio observations (Hjellming 1985, private communication; see also Cassatella *et al.* 1985).

Observations also provide strong evidence suggesting that the outburst occurs on a time scale which is less than or comparable with a dynamical time scale.

1. *The high luminosity at outburst.*—Observations of RS Oph outbursts reveal that at maximum $\bar{V}_{\rm out} \approx 4.6$ ($V_{\rm max} = 4.3$ in 1933; $V_{\rm max} = 5$ in 1958; not well covered in 1967; $V_{\rm max} = 5.7$ in 1985, but the maximum here was probably missed by 1 day; Cassatella *et al.* 1985). The mean magnitude at minimum is $\bar{V}_{\rm min} \approx 11.5$. If we adopt, for the giant companion, $M_{v,g} = -2.50$ (-1.91) we then have for the outburst luminosity at maximum $L_{\rm out} \gtrsim 4.7 \times 10^5\ L_\odot$ ($3.0 \times 10^5\ L_\odot$). Even if the distance were taken to be $d = 1.6$ kpc (rather than 3 kpc) we would obtain a high luminosity estimate $L_{\rm out} \gtrsim 1.2 \times 10^5\ L_\odot$ ($8 \times 10^4\ L_\odot$). For comparison, the Eddington luminosity (for electron scattering opacity and a pure hydrogen composition) is

$$L_{\rm E} \approx 3.3 \times 10^4\ L_\odot \left(\frac{M}{M_\odot}\right).$$

It is thus apparent that RS Oph exhibited a strongly supercritical luminosity at maximum.

2. *The extremely sharp rise to maximum.*—The abrupt rise to optical maximum exhibited in all observed outbursts is further suggestive of an extremely dynamic event.

3. *The large velocities of ejection.*—Observations of RS Oph have also provided evidence for large velocities. An expansion velocity of 3540 km s^{-1} was indicated by the displacement of absorption features in the 1958 outburst (Bloch and Dufay 1958). Also, for the 1958 outburst, absorption components were identified at velocities of -400, -2500, and -4500 km s^{-1} (Folkart, Pecker, and Pottasch 1965; Tolbert, Pecker, and Pottasch 1967). Blue H absorptions at -2700 km s^{-1} and -3900 km s^{-1} were also determined for the 1967 outburst (Barbon, Mammano, and Rosino 1968). Finally, radio observations of the 1985 outburst indicate velocities of a few thousand km s^{-1} in at least one radio blob (Hjellming, private communication).

III. POSSIBLE MODELS FOR RS OPHIUCHI

The recurrent novae have historically been considered to represent a class of objects intermediate between the dwarf novae and the classical novae (Payne-Gaposchkin 1957). 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. In this section we will identify and examine various possible models for the recurrent nova RS Oph.

a) The Thermonuclear Runaway Model

The considerable success which has been achieved in explaining classical novae in the context of the thermonuclear runaway model (Truran 1982), coupled with the facts that both the peak luminosities for recurrent novae systems (like RS Oph in outburst) and the integrated outburst energies are significantly higher than those of the dwarf novae, leads us first to examine whether a thermonuclear model is compatible with our existing knowledge of RS Oph. We note at the outset that the most severe challenge to this model is provided by the need to explain the short recurrence time scales for the recurrent novae in general (~ 10–100 yr) and for RS Oph in particular (~ 10–30 yr). In contrast, classical nova outbursts are estimated to recur on time scales of thousands to hundreds of thousands of years.

It is instructive to ascertain whether such short recurrence periods can characterize thermonuclear runaway events and, if so, under what restricted conditions. The basic requirement is the accumulation of sufficient matter on the white dwarf to trigger ignition and runaway. Holding all other factors constant, the recurrence interval can generally be shortened by any or all of the following: (1) increasing the white dwarf mass, thus reducing the envelope mass required for ignition; (2) increasing the white dwarf luminosity, thus increasing the temperature at the base of the envelope and thereby reducing the envelope mass required for ignition; and (3) increasing the rate of mass transfer and therefore the rate of growth of the accreted hydrogen envelope. Indeed, by making appropriate if somewhat limiting assumptions for the white dwarf mass and luminosity and for the accretion rate, recurrence intervals in the range ~ 30–100 yr can be achieved (Starrfield, Sparks, and Truran 1985). It remains to ask whether the requisite conditions are compatible with other observed properties of the systems in question.

In order to examine the particular case of RS Oph, we proceed as follows. Guided by numerical studies (Starrfield, Sparks, and Truran 1985; Prialnik *et al.* 1982), we assume a critical pressure sufficient to initiate runaway

$$P_{\rm crit} \approx 2 \times 10^{19}\ {\rm dyne\ cm^{-2}}\ . \tag{1}$$

This is then related to the critical mass of accreted envelope matter required to trigger runaway by the relation (Fujimoto 1982; MacDonald 1983)

$$\Delta M_{\rm crit} = \frac{4\pi}{G}\frac{R_{\rm WD}^4}{M_{\rm WD}} P_{\rm crit} \approx 5.9 \times 10^{-5}\ M_\odot \left(\frac{R_{\rm WD}}{5 \times 10^8\ {\rm cm}}\right)^4 \left(\frac{M_{\rm WD}}{M_\odot}\right)^{-1} \left(\frac{P_{\rm crit}}{2 \times 10^{19}\ {\rm dyne\ cm^{-2}}}\right). \tag{2}$$

For the limiting case of a massive white dwarf of $M_{\rm WD} = 1.38\ M_\odot$ and $R_{\rm WD} = 1.9 \times 10^8$ cm, this gives $\Delta M_{\rm crit} \approx 8.9 \times 10^{-7}\ M_\odot$. Adopting an "average" recurrence interval for RS Oph of ~ 20 yr, we arrive at the accretion rate necessary to fuel the recurrent outbursts of RS Oph:

$$\dot{M}_{\rm crit} \approx \frac{\Delta M_{\rm crit}}{\tau_{\rm rec}} \approx 3 \times 10^{-6}\ M_\odot\ {\rm yr}^{-1} \left(\frac{R_{\rm WD}}{5 \times 10^8\ {\rm cm\ s}^{-1}}\right)^4 \left(\frac{M_{\rm WD}}{M_\odot}\right)^{-1} \left(\frac{P_{\rm crit}}{2 \times 10^{19}\ {\rm dyne\ cm}^{-2}}\right) \left(\frac{\tau_{\rm rec}}{20\ {\rm yr}}\right)^{-1}, \quad (3)$$

which gives $\dot{M}_{\rm acc} \approx 4.45 \times 10^{-8}\ M_\odot\ {\rm yr}^{-1}$ for the limiting case defined by $M_{\rm WD} = 1.38\ M_\odot$ and $R = 1.9 \times 10^8$ cm.

We now ask whether an accretion rate in this range is compatible with other observed features of this system. To this goal, we first examine accretion from the giant's wind. The velocities characteristic of this system are the following:

Orbital velocity:

$$V_{\rm orb} \approx 5.6 \times 10^6\ {\rm cm\ s}^{-1} \left(\frac{M_1 + M_2}{4\ M_\odot}\right)^{1/3} \left(\frac{P}{230\ {\rm d}}\right)^{-1/3}. \quad (4)$$

Wind velocity:

$$V_{\rm wind} \approx V_{\rm esc} \approx 1.07 \times 10^7\ {\rm cm\ s}^{-1} \left(\frac{M_1}{3\ M_\odot}\right)^{1/2} \left(\frac{R_1}{100\ R_\odot}\right)^{-1}. \quad (5)$$

Relative velocity:

$$V_{\rm rel} \approx (V_{\rm orb}^2 + V_{\rm esc}^2 + V_S^2)^{1/2} \approx 1.2 \times 10^7\ {\rm cm\ s}^{-1}, \quad (6)$$

where we have assumed the square of the sound speed in the wind, V_S^2, to be negligible. The rate of mass accretion from the wind is then given by (Bondi and Hoyle 1944; Livio *et al.* 1986)

$$\dot{M}_{\rm acc} \approx \pi R_A^2 \rho_w(a) V_{\rm rel} \approx \frac{4\pi (G M_2)^2 \rho_w}{(V_{\rm orb}^2 + V_{\rm esc}^2)^{3/2}}, \quad (7)$$

where R_A is the accretion radius and a is the separation.

Assuming $V_{\rm wind}$ = constant = $V_{\rm esc}$, we also have for the rate of wind mass loss

$$\dot{M}_W \approx 4\pi r^2 \rho_w V_{\rm esc}. \quad (8)$$

From equations (7) and (8) we can express the rate of wind mass loss as

$$\dot{M}_W \approx \frac{a^2 V_{\rm esc}(V_{\rm orb}^2 + V_{\rm esc}^2)^{3/2}}{(G M_2)^2} \dot{M}_{\rm acc} \approx 58 \left(\frac{a}{10^{13}\ {\rm cm}}\right)^2 \left(\frac{V_{\rm esc}}{10^7\ {\rm cm\ s}^{-1}}\right) \left(\frac{V_{\rm rel}}{10^7\ {\rm cm\ s}^{-1}}\right)^3 \left(\frac{M_{\rm WD}}{M_\odot}\right)^{-2} \dot{M}_{\rm acc}. \quad (9)$$

We may use this expression to determine the rate of wind driven mass loss necessary to provide the critical accretion rate we obtained in equation (3):

$$\dot{M}_W = 1.7 \times 10^{-4}\ M_\odot\ {\rm yr} \left(\frac{R_{\rm WD}}{5 \times 10^8\ {\rm cm}}\right)^4 \left(\frac{P_{\rm crit}}{2 \times 10^{19}\ {\rm dyne\ cm}^{-2}}\right) \left(\frac{M_{\rm WD}}{M_\odot}\right)^{-3} \left(\frac{a}{10^{13}\ {\rm cm}}\right)^2 \left(\frac{V_{\rm esc}}{10^7\ {\rm cm\ s}^{-1}}\right) \left(\frac{V_{\rm rel}}{10^7\ {\rm cm\ s}^{-1}}\right)^3 \left(\frac{\tau_{\rm rec}}{20\ {\rm yr}}\right)^{-1}. \quad (10)$$

For the specific choice of conditions given by $M_{\rm WD} = 1.38\ M_\odot$, $R_{\rm WD} = 1.9 \times 10^8$ cm, and $a = 1.75 \times 10^{13}$ cm ($M_1 = 3\ M_\odot$, $P = 230$ yr), we find that we require a rate of wind driven mass loss:

$$\dot{M}_W \approx 7.6 \times 10^{-6}\ M_\odot\ {\rm yr}^{-1}. \quad (11)$$

For purposes of comparison, we note the rate of wind mass loss for red giants from Kudritzki and Reimers (1978) is given by

$$\dot{M}_W \approx 5.5 \times 10^{-13}\ M_\odot\ {\rm yr}^{-1} \left(\frac{L_1}{L_\odot}\right) \left(\frac{R_1}{R_\odot}\right) \left(\frac{M_1}{M_\odot}\right)^{-1}, \quad (12)$$

which for the case of the giant in the RS Oph system gives

$$\dot{M}_W \approx 3.67 \times 10^{-8}\ M_\odot\ {\rm yr}^{-1} \left(\frac{L_1}{2000\ L_\odot}\right) \left(\frac{R_1}{100\ R_\odot}\right) \left(\frac{M_1}{3\ M_\odot}\right)^{-1}. \quad (13)$$

Comparison of the expected wind mass-loss rate from equation (13) with the required rate from equation (11) indicates that accretion only from a wind is unlikely to be able to satisfy the requirements for a thermonuclear runaway interpretation of the outbursts of RS Oph.

If we nevertheless *assume* that a thermonuclear runaway is achievable in the presence of such a high accretion rate (by Roche lobe overflow), we encounter additional problems. Even for the case of an extremely massive white dwarf ($M_{\rm WD} = 1.38\ M_\odot$, $R_{\rm WD} \approx 1.9 \times 10^8$ cm), a very high average accretion rate $\langle \dot{M}_{\rm acc} \rangle \approx 4.45 \times 10^{-8}\ M_\odot\ {\rm yr}^{-1}$ is required (see eq. [3]). *If accretion is further assumed to proceed at a constant rate*, we would then have an accretion luminosity

$$L_{\rm acc} \approx 2.7 \times 10^{36}\ {\rm ergs\ s}^{-1} \approx 715\ L_\odot, \quad (14)$$

and, in a steady disk situation, we would expect *at quiescence* to find temperatures of order

$$T_{\rm disk} \approx \left\{\frac{3GM\dot{M}}{8\pi R^3\sigma}\left[1-\left(\frac{R_*}{R}\right)^{1/2}\right]\right\}^{1/4} \approx 6.3\times 10^5\ {\rm K}\left(\frac{R}{1.9\times 10^8\ {\rm cm}}\right)^{-3/4} . \quad (15)$$

The implied luminosity and high temperature are entirely incompatible with observations of the system at quiescence: e.g., He II $\lambda4686$ is barely present in the spectrum. It should be remembered that the entire system is embedded in a shell (e.g., Wallerstein 1963), and thus even radiation emitted in the UV should be absorbed and reemitted at longer wavelengths. Adams, Humason, and Joy (1927) found bright H Balmer and faint Fe II in emission, superposed on a G5 absorption spectrum. Swings and Struve (1941, 1943) noted sharp emission lines, Sanford (1947) found only H Balmer in emission, and Merrill and Bowen (1951) identified a few emission lines of Fe II and O I. More recent spectra have been provided by Barbon, Mammano, and Rosino (1968), Wallerstein (1963), Wallerstein and Cassinelli (1968), and Sahade, Brandi, and Fontenlo (1984). In general, the spectrum of RS Oph at quiescence is more consistent (if anything) with accretion onto a main-sequence star (e.g., Kenyon and Webbink 1984, Fig. 7) rather than with accretion onto a white dwarf (e.g., Kenyon and Webbink 1984, Fig. 8). The system at quiescence resembles T CrB, which is believed to contain a main-sequence companion (Kenyon and Garcia 1986).

b) Models Involving a Disk

Models involving disk accretion onto a white dwarf or a main-sequence star may generally be of two types: disk instability models and models involving a mass transfer event into a disk. We discuss each of these alternatives below. We first note that such models generally encounter severe difficulties in explaining the extremely rapid (dynamic time scale) evolution of RS Oph in outburst that we have reviewed previously. This is a fundamental problem which, as we shall see below, arises from the fact that disk decay proceeds on a viscous time scale and acts to constrain disk models for the outbursts of RS Oph.

i) *Disk Instability Models*

Disk instability models are generally built upon the assumption that mass is stored in the accretion disk (or ring) during periods of quiescence and that subsequently the gravitational potential energy is released as the disk becomes unstable. For this type of model to work and to supply the entire outburst energy, we would require a mass in the disk as it becomes unstable of order

$$\Delta M_d \approx 1.8\times 10^{-6}\ M_\odot \left(\frac{M_{\rm WD}}{M_\odot}\right)^{-1}\left(\frac{R_{\rm WD}}{5\times 10^8\ {\rm cm}}\right)\left(\frac{E_{\rm tot}}{10^{45}\ {\rm ergs}}\right) , \quad (16)$$

where $E_{\rm tot}$ is the total energy release associated with the outburst. A significantly higher disk mass would, of course, be required if (as, for example, for the case of T CrB) the accreting star is not a white dwarf.

The main problem associated with this type of model—assuming that recurrence times as long as $\sim$20 yr can at all be accomodated in this framework—is that the energy is released on a time scale comparable to the diffusion time through the disk (e.g., Bath and Pringle 1981)

$$\tau_v \approx (3.2\times 10^7\ {\rm s})\,\alpha^{-4/5}\left(\frac{\dot{M}}{5\times 10^{21}\ {\rm g\ s^{-1}}}\right)^{-3/10}\left(\frac{M}{M_\odot}\right)^{1/4}\left(\frac{R_d}{10^{13}\ {\rm cm}}\right)^{5/4}\left(\frac{\gamma}{5/3}\right)^{-1} , \quad (17)$$

where we have scaled the accretion rate with 10 $\dot{M}_{\rm crit}$ for a white dwarf (lower accretion rates result in a longer time scale), and we have used Kramer's opacity in the disk. The time scale obtained from equation (17) is clearly in conflict with the observed sharp rise of RS Oph in outburst. Even if somewhat larger diffusion velocities were obtained (by a factor $\sim R/H$) because of large radial temperature gradients (e.g., Lin, Papaloizou, and Faulkner 1985), the extremely rapid outburst development (which, as we have indicated, occurs on a dynamical time scale) would still be extremely difficult to explain.

ii) *Models Involving a Mass Transfer Event into a Disk or Mass Which Circularizes into a Ring*

Webbink (1976) has proposed a model for the outbursts of the recurrent nova T CrB which holds potentially important implications for RS Oph as well. In this model, a blob of matter is transferred from the giant star; the mass stream either encounters and shocks itself after passing around the accreting star (e.g., Lubow and Shu 1975) or impinges onto a preexisting accretion disk. The difficulty with either of these two possibilities is the fact that *one would anticipate the occurrence of a secondary peak*, similar to that observed in the case of T CrB, which results from the formation of a disk and subsequent disk decay onto the white dwarf. The secondary peak in this picture should appear approximately a viscous time scale τ_v later than the initial outburst peak, which is presumably attributable either to energy release associated with the circularization of the ring or to the energy released in the shocked gas at the impact point. The height of the secondary peak should then reflect the depth of the gravitational potential of the accreting object; for the case of an accreting white dwarf rather than a main-sequence star, this peak would then be expected to be much higher than the one observed in the outbursts of T CrB. In fact, *no such secondary peak has been identified in any of the observed outbursts of RS Oph.*

If one chooses alternatively to assume simply an increased rate of mass transfer into a disk, rather than the transfer of a blob of matter, the time scale again serves to impose a severe constraint. Here again, the entire outburst signature should be dictated by the viscous time scale for the disk, which, as we have noted previously, appears to be too long to be consistent with the outbursts of RS Oph.

IV. A CONSISTENT MODEL FOR RS OPHIUCHI

We present in this section a model for the outbursts of RS Oph which we find to be consistent with all existing observations. We have been guided toward this picture by a number of basic points which have arisen in our scrutiny of other possible models: (1)

unless some extremely unusual means exists for hiding a hot and luminous rapidly accreting massive white dwarf at quiescence, the RS Oph outbursts cannot be attributable to thermonuclear runaways; (2) the outburst must proceed on a dynamical time scale; (3) the outburst cannot involve an accretion disk as a mediator to an accretion event; (4) the similarity of this system to that of T CrB (the period, the nature of the giant companion, and, particularly, the outburst spectroscopic characteristics) suggests a possible similarity in the outburst mechanism; and (5) radio observations of a "jet" (or at least an asymmetric blob) may suggest a non–spherically symmetric event.

Proceeding by analogy with T CrB, we then begin with the assumption that the giant star in the RS Oph system episodically transfers a chunk of matter (Webbink 1976). We can attempt, at least in principle, to identify the outburst peak in RS Oph either with the main (first) outburst in T CrB or with the secondary outburst. In both instances, however, we encounter severe difficulties. If identification with the first feature is correct (matter colliding with and shocking itself and circularizing, or impinging onto an accretion disk), then we would anticipate a delayed secondary peak which is absent in RS Oph. If identification with the secondary outburst feature of T CrB is correct (assuming the presence of an accreting white dwarf, to account for the higher luminosity and energy output in the outburst), then we would expect both a precursor peak (associated with matter shocking itself) and a less rapid rise time (associated with disk accretion), again contradicting the observations.

These difficulties can be circumvented if the minimum distance of the orbit of the transferred mass from the accreting star, given by (an approximation of Ulrich and Burger 1976 to the results of Lubow and Shu 1975)

$$r_{\min} \approx 8.2 \times 10^{11}\ \mathrm{cm}\left(\frac{a}{1.88 \times 10^{13}\ \mathrm{cm}}\right)\left[\frac{M_2/M_1}{2/3} + \left(\frac{M_2/M_1}{2/3}\right)^2\right]^{1/4}, \tag{18}$$

is sufficiently small. If $R_2 \gtrsim r_{\min}$, i.e., the recipient is a puffed-up main-sequence star, then *the stream hits the accreting star directly, and only one outburst (accretion) peak will be observed.* We shall now proceed to demonstrate that this is in fact a very plausible scenario.

If we assume $R_2 \approx r_{\min}$, then the amount of mass that must be transferred to produce the observed outburst energy is

$$\Delta M_t \approx 1.5 \times 10^{-3}\ M_\odot \left(\frac{E_{\mathrm{tot}}}{10^{45}\ \mathrm{ergs}}\right)\left(\frac{R_2}{8.2 \times 10^{11}\ \mathrm{cm}}\right)\left(\frac{M_2}{2\ M_\odot}\right)^{-1}, \tag{19}$$

which is ~ 3 times that required in T CrB (Webbink 1976). The maximum matter ejection velocity can be obtained by assuming adiabatic shock acceleration from the colliding stream of matter into the existing circumstellar material (resulting from the giant's wind)

$$v_{\mathrm{shock}} \approx \left(\frac{2GM_2}{R_2}\right)^{1/2}\left(\frac{\rho_{\mathrm{wind}}}{\rho_{\mathrm{stream}}}\right)^{-\{2+[2\gamma/(\gamma-1)]^{1/2}\}^{-1}}. \tag{20}$$

The density of the stream can be estimated from

$$\rho_{\mathrm{stream}} \approx \frac{3\Delta M_t}{4\pi(v_{\mathrm{ff}}\,\Delta t)^3} \approx \frac{3}{4\pi}\left(\frac{R_2}{2GM_2}\right)^{3/2}\frac{\Delta M_t}{(\Delta t)^3}, \tag{21}$$

where v_{ff} is the free-fall velocity at the surface of the accreting star and Δt is the impact duration. The form of the light curve (rapid rise and brief maximum) suggests that the energy input occurs on a time scale $\Delta t \lesssim 3$ days, giving $\rho_{\mathrm{stream}} \gtrsim 1.7 \times 10^{-9}$ g cm^{-3}. The density in the wind is

$$\rho_{\mathrm{wind}} \approx \frac{\dot{M}_{\mathrm{wind}}}{4\pi a^2 v_{\mathrm{esc}}} \approx 6 \times 10^{-17}\ \mathrm{g\ cm^{-3}}, \tag{22}$$

where we have adopted the Kudritzki and Reimers (1978) mass-loss formula (eq. [12]). We then obtain, for a radiation-dominated shock, a maximum velocity $v_{\mathrm{shock}} \gtrsim 9000$ km s^{-1}, which is more than adequate to produce the observed maximum velocities given the approximate nature of our estimate (the density in the existing shell can be somewhat higher than estimated by eq. [22] because of matter from the previous outburst, and we have neglected ionization and radiative losses in the shock).

We also note that this picture naturally allows for the existence of an intrinsic deviation from spherical symmetry.

A further point of consistency arises from a consideration of the temperature of the accreting star at quiescence. For our estimate of the giant's luminosity, the accreting star has to contribute a luminosity $L \approx 1000\ L_\odot$ at minimum. In the absence of high-excitation circumstellar emission, we must conclude that the effective temperature cannot exceed $\sim 10^4$ K. In the picture we have proposed involving an inflated accretor, $R_2 \gtrsim 8.2 \times 10^{11}$ cm, and hence $T_e \lesssim 9500$ K, a value quite consistent with observations.

A critical question to be addressed here is whether it is realistic to assume that the accreting star has a radius of order $\sim 12\ R_\odot$. To answer this question, we must consider the response of the accreting star to mass accretion. Kippenhahn and Meyer-Hofmeister (1977; see also Benson 1970 and Ulrich and Burger 1976) have calculated the radii of accreting main-sequence stars. For a constant accretion rate of $10^{-4}\ M_\odot$ yr^{-1}, they find that an accreting star of 2 $M_\odot$ will achieve a maximum radius of ~ 16 times its main-sequence radius; the degree of expansion increases as the accreting star's mass decreases in this range. They also find that a radius of $\sim 12\ R_\odot$ is achieved by an accreting 2 $M_\odot$ star after less than $\sim 0.25\ M_\odot$ has been accreted—which would require ~ 150 events.

These numbers are encouraging with respect to our picture. There are nevertheless several points which should be examined more carefully. We first note that Kippenhahn and Meyer-Hofmeister have assumed in their calculations that *the accreted matter cools in* *the accretion process and arrives at the stellar surface with the same entropy as the material at the photosphere.* If this assumption is relaxed, which is probably necessary for the case of a dynamical accretion event of the type we are describing, then the expansion of the accreting star can be expected to be considerably more pronounced (see, e.g., the calculations of Sarna 1984 and Prialnik and Livio 1985).

We also note that while the *average* accretion rate according to our picture is of the order of $\Delta M_t/\tau_{\rm rec} \approx 10^{-4}\ M_\odot\ {\rm yr}^{-1}$, this accretion is expected to proceed episodically, rather than at a constant rate, with a much lower accretion rate characterizing the intervals between outbursts. This introduces uncertainties into our comparisons with the results of Kippenhahn and Meyer-Hofmeister (1977). It is in fact the compression of the original envelope of the underlying star which is the critical factor in setting the thermal relaxation time scale. The mass of the envelope over which significant compression is realized is expected to be of the order of the total accreted mass. We therefore estimate that the envelope of the accreting star can be expected to regain equilibrium on a time scale of order $\tau_{\rm th}$,

$$\tau_{\rm th} \approx \frac{GM_2\,\Delta M_t}{R_2 L_2}\left(\frac{\Delta R}{R_2}\right), \tag{23}$$

where ΔR is the spatial extent of the envelope. For our assumed parameters of the RS Oph system, we obtain

$$\tau_{\rm th} \approx 1500\ {\rm yr}\left(\frac{M_2}{2\ M_\odot}\right)\left(\frac{\Delta M_t}{0.25\ M_\odot}\right)\left(\frac{R_2}{8.2\times 10^{11}\ {\rm cm}}\right)^{-1}\left(\frac{L_2}{1000\ L_\odot}\right)^{-1}\left(\frac{\Delta R}{R_2}\right). \tag{24}$$

This would appear to indicate that, indeed, for the short recurrence times observed for RS Oph the secondary remains inflated.

It is interesting to conjecture that RS Oph simply represents a slightly more advanced evolutionary phase of a T CrB–like binary. Models of the evolutionary status of T CrB (Webbink 1979) indicate that it is probably in the very early phases of mass exchange which will ultimately accelerate to dynamical time scale mass transfer. In RS Oph, the mean mass transfer rate is an order of magnitude higher (4 times the recurrence rate, with 3 times as much mass transferred per event), implying that several times as much material has been transferred already as in the case of T CrB ($\dot{M} \sim \Delta M_t^3$ for the early phases of dynamical time scale mass transfer; e.g. Paczyński and Sienkiewicz 1972). Thus the secondary in T CrB has not yet accreted enough material to reach the bloated state of that in RS Oph, and the stream is able to pass around the secondary star without hitting it directly.

V. DISCUSSION AND CONCLUSIONS

Our aim in this paper has been to advance a model for the outbursts of the recurrent nova RS Oph which is both compatible with known observational constraints and consistent with our theoretical knowledge of the behavior of related cataclysmic variable systems. In the process, we have reviewed the observed properties of RS Oph in and out of outburst and discussed how these properties serve to constrain theoretical models for the outburst. We have indicated why most "standard" models fail in one manner or another to meet the imposed requirements. We draw the following general conclusions from this investigation:

1. The short recurrence time scale for the outbursts of RS Oph imposes a severe constraint on any thermonuclear runaway model for these events. A high accretion rate is thereby demanded for the system in between outbursts, in order to reconstitute a sufficient hydrogen envelope to trigger a runaway on the necessary time scale. The implied luminosity and effective temperature are incompatible with observations of the system in quiescence. We thus conclude that a thermonuclear runaway model is not appropriate for this system.
2. Disk models for the outbursts of RS Oph are most severely constrained by the fact that these outbursts are observed to proceed on a dynamical time scale, while disk decay is expected to occur on a diffusion time scale. We do not see how such models can be made to reproduce the extremely rapid development of the light curve of RS Oph.
3. The striking similarities in the properties of the RS Oph and T CrB systems in and out of outburst are suggestive of the fact that a similar outburst mechanism may be appropriate.
4. Our proposed model for RS Oph, which involves an episodic accretion event and bears many similarities to the model proposed by Webbink (1976) for the outbursts of T CrB, is found to be consistent with all available observations of this recurrent nova system. We find it particularly attractive that the differences in the outburst characteristics of RS Oph and T CrB can be essentially understood on the basis of the difference in evolutionary status of the accreting star, resulting from a factor ~ 10 in their mean mass transfer rates. This suggests that the accreting star in T CrB has accreted much less matter than that in RS Oph, and consequently has yet to evolve to so bloated a state in response to mass accretion. Thus the accretion stream can pass around the star in T CrB: disk formation and decay are then allowed to occur. In contrast, the higher mean mass transfer rate in RS Oph implies also a larger total mass accreted, leaving the accreting star in a sufficiently expanded configuration that the accretion stream impacts the star directly on its first pass.
5. We have been concerned in this paper with the main outburst mechanism for RS Oph. We have not addressed the question of the interactions of the ejecta with the surrounding nebular matter which is seen to be associated with this system (e.g., Pottasch 1967; Bode and Kahn 1985). We nevertheless believe it is important to note that our model is consistent with observed behaviors.
6. We also note that our model is compatible with such asymmetric effects as have recently been inferred from radio observations (Hjellming 1985, private communication).

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M. LIVIO, J. W. TRURAN, and R. F. WEBBINK: Department of Astronomy, University of Illinois, 1011 W. Springfield, Urbana, IL 61801