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Resumption of mass accretion in RS Oph

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ABSTRACT

The latest outburst of the recurrent nova RS Oph occurred in 2006 February. Photometric data presented here show evidence of the resumption of optical flickering, indicating re-establishment of accretion by day 241 of the outburst. Magnitude variations of up to 0.32 mag in V band and 0.14 mag in B band on time-scales of 600–7000 s are detected. Over the two-week observational period, we also detect a 0.5 mag decline in the mean brightness, from $V \approx 11.4$ to 11.9, and record $B \approx 12.9$ mag. Limits on the mass accretion rate of $\sim 10^{-10} \leqslant \dot{M}_{\rm acc} \leqslant 10^{-9}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$ are calculated, which span the range of accretion rates modelled for direct wind accretion and Roche lobe overflow mechanisms. The current accretion rates make it difficult for thermonuclear runaway models to explain the observed recurrence interval, and this implies average accretion rates are typically higher than seen immediately post-outburst.

Key words: binaries: symbiotic – stars: individual: RS Oph – stars: mass-loss – novae, cataclysmic variables – stars: winds, outflows.

1 INTRODUCTION

Recurrent novae (RNe) are interacting binary systems in which multiple nova outbursts have been observed. Both thermonuclear runaway and accretion models have been hypothesized as the outburst mechanism in these systems (Kenyon 1986). While thermonuclear runaway is generally the preferred mechanism, there are problems with the high accretion rate required given the short outburst recurrence interval. The recurrent nova (RN) RS Ophiuchi has undergone six recorded outbursts in the last 108 yr (Oppenheimer & Mattei 1993), the most recent occurring on 2006 February 12, which we take as day 0 (Hirosawa et al. 2006). RS Oph consists of a white dwarf primary accreting material from a red giant secondary within a nebula formed from the red giant wind. Attempts to classify the secondary component have resulted in suggestions ranging from K0 III (Wallerstein 1969) to M4 III (Bohigas et al. 1989) with several concluding M2 III to be most likely (Barbon, Mammano & Rosino 1969; Rosino, Bianchini & Rafanelli 1982; Bruch 1986; Oppenheimer & Mattei 1993). The white dwarf in the system is close to the Chandrasekhar mass limit (Dobrzycka & Kenyon 1994); hence, the ratio of mass accreted to mass ejected will determine whether RS Oph is a potential Type Ia supernova progenitor (Sokoloski et al. 2006).

The quiescent characteristics of RS Oph have led to its classification as a symbiotic star, although with a weak hot-component spectrum. Most symbiotic stars do not exhibit the variability on time-scales of minutes seen in cataclysmic variables (Sokoloski, Bildsten & Ho 2001), yet short time-scale, aperiodic variations in optical brightness have long been known in RS Oph in its quiescent state (Bruch 1986). These stochastic or aperiodic brightness variations are known as flickering, with 'strong' flickering being of the order of a few tenths of magnitudes (Sokoloski et al. 2001). While symbiotic stars are a heterogenous class, other members show similarities to RS Oph that are applicable here.

To date, there have been no reported observations of the re-establishment of optical flickering in the immediate post-outburst phase of a RN, a fact that contributes to our uncertainty of the nature of the outburst mechanism. Observations by Zamanov et al. (2006) on day 117 (2006 June 9) show no flickering of amplitude above 0.03 mag in B band, from which they conclude that an accretion disc around the white dwarf has been destroyed as a result of the 2006 outburst. The light curve reached a post-outburst minimum in 2006 September. Following discovery of re-brightening (Bode et al. 2006a), we monitored RS Oph photometrically for two weeks in B and V bands, detecting the resumption of optical flickering (Worters et al. 2006).

2 OBSERVATIONS

Observations of duration 37–118 min were made on 11 nights between 2006 October 11 and 24, the shorter observations being curtailed by cloud. Observations were made with the South African Astronomical Observatory (SAAO) 1-m telescope and the SAAO CCD camera, a 1024 × 1024 pixel SITe back-illuminated

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Table 1. Observations made using the SAAO 1-m telescope and SAAO CCD. T is the total duration of each night's observations, t_{exp} is the exposure time, τ is the time-scale over which flickering significances (R_{var}) and amplitudes (A) are calculated. Values enclosed in square brackets are standard deviations of $\bar{R}_{\mathrm{var}}$.

Date	JD (mid-observations)	Day of outburst	Filter (Johnson)	T (min)	t_{exp} (s)	$\bar{V}$ (mag)	$\bar{R}_{\mathrm{var}}$ (τ = 10 min)	R_{var} ($\tau = T$)	$\bar{A}$(mag) (τ = 10 min)	A (mag) ($\tau = T$)
2006 October 11	245 4020.24	241	V	68	10	11.40	2.38 [0.91]	1.99	0.06	0.06
2006 October 13	245 4022.27	243	V	51	10	11.52	2.37 [1.08]	3.21	0.06	0.10
2006 October 15	245 4024.26	245	V	50	10	11.50	1.83 [0.55]	2.00	0.07	0.09
2006 October 16	245 4025.26	246	V	56	10	11.56	3.37 [0.83]	5.56	0.07	0.12
2006 October 17	245 4026.25	247	B	52	20, 40, 90	12.86	3.30 [1.39]	2.40	0.14	0.14
2006 October 19	245 4028.27	249	V	73	10	11.65	2.93 [1.64]	4.68	0.10	0.20
2006 October 20	245 4029.25	250	V	37	10	11.67	2.40 [0.67]	4.30	0.07	0.14
2006 October 21	245 4030.28	251	V	118	10,30	11.64	3.49 [2.90]	4.34	0.21	0.32
2006 October 22	245 4031.26	252	V	77	10	11.81	2.91 [0.91]	4.00	0.09	0.14
2006 October 23	245 4032.27	253	V	109	10	11.84	4.54 [1.91]	12.02	0.10	0.29
2006 October 24	245 4033.26	254	V	100	10	11.88	2.51 [1.20]	5.50	0.08	0.31

chip. The field of view is 5 × 5 arcmin^2, which is sufficient to include several comparison stars close to the target, including USNO-B1.0 0833−0368817 and −0368883. Integration times were typically 10 s in Johnson V (20 s in Johnson B), with a readout time of 19 s, allowing continuous V-band monitoring with a temporal resolution of ∼30 s. Longer exposure times were occasionally used to compensate for poorer sky conditions. Details of each night's observations are given in Table 1. The three nights lacking data were lost due to clouds.

Preliminary data reduction was performed using standard procedures in IRAF. The resulting images were then processed using CCD tasks in the SAAO STAR package (described in Balona 1995; Crause, Balona & Kurtz 2000) to determine aperture magnitudes of the target and selected comparison stars.

3 RESULTS

Fig. 1 shows the diversity of flickering amplitude and time-scale present in the V-band light curves obtained on 10 nights of the two-week period of observations. Visual inspection reveals an increase in flickering amplitude during nights towards the end of the run.

Figs 2 and 3 show differential light curves of RS Oph compared with two comparison stars in the field for the nights during which we detect some of the smallest and the greatest flickering amplitudes, respectively. Comparing the weakest flickering detected in the target (Fig. 2) with brightness variations in the constant comparison stars verifies the intrinsic variability of RS Oph. Flickering is also detected in the B-band data, plotted in Fig. 4.

Gromadzki et al. (2006) observed a selection of symbiotic stars, performing a statistical evaluation of the significance of flickering in the data. They calculated mean magnitudes and standard deviations in their variable targets (σ_{var}) and comparison stars (σ_{comp}). Since the comparison stars in the field are all ⩾2 mag fainter than RS Oph, standard deviations on the value expected for a constant star of the same brightness as the target (σ'_{comp}) are derived from an empirical formula. With the number of counts in the data presented here being significantly lower than the Gromadzki et al. (2006) values (a few 1000 s, cf. 10^5), this method proved less reliable when applied to our data. Two alternative methods of deriving σ'_{comp} were used in the current analysis: (i) fitting a power law to the mean magnitude and σ_{comp} values for the comparison stars, obtaining an estimate of σ'_{comp} in RS Oph by extrapolation and (ii) estimating σ'_{comp} by equating it to σ_{comp} for the brightest comparison star (13.2 mag), thus yielding very conservative values. All results presented here were obtained using (ii), the more conservative technique, giving larger error bars.

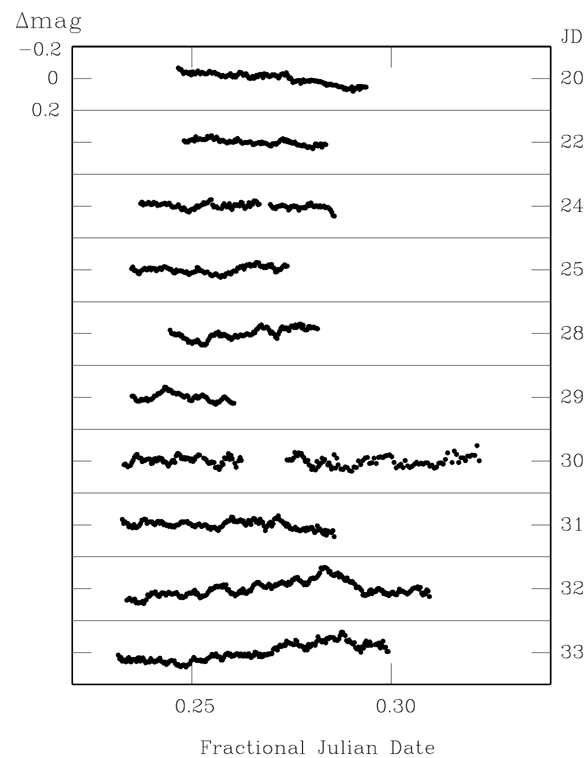

Figure 1. 10 nights' differential V-band light curves of RS Oph. Magnitudes are normalized to the mean value for each night to illustrate relative flickering amplitudes. Numbers down the right-hand margin are JD − 245 4000. The break in data points on the night labelled JD = 30 is due to cloud.

The ratio $R_{\mathrm{var}} = \sigma_{\mathrm{var}}/\sigma'_{\mathrm{comp}}$ can be used to assess the significance of the flickering. The criteria specified by Gromadzki et al. (2006) to determine the existence of flickering are as follows:

(i) $1.5 \leqslant R_{\mathrm{var}} < 2.5$ – flickering 'probably present' and
(ii) $2.5 \leqslant R_{\mathrm{var}}$ – flickering 'definitely present'.

Evaluating the full data set for each night according to the above criteria suggests that flickering is definitely evident in RS Oph on all, but three nights observed. Even using the conservatively large error estimates, R_{var} is close to the cut-off value for definite flickering on

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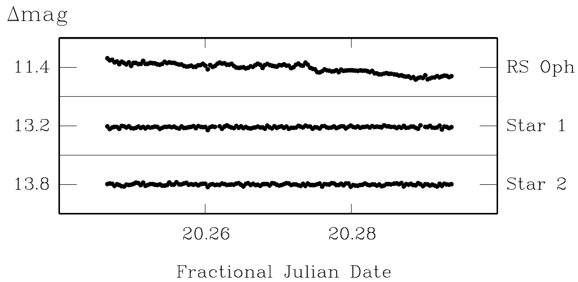

Figure 2. *V*-band light curves of RS Oph and two comparison stars from 2006 October 11, when the weakest flickering was detected. The ordinate for each plot spans 0.4 mag. Amplitude variability of 0.06 mag is evident in the target.

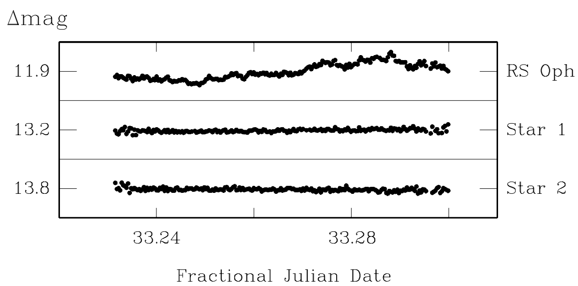

Figure 3. Example *V*-band light curves of RS Oph and two comparison stars in the field. These data are taken from 2006 October 24, one of the nights showing the strongest flickering observed with amplitude 0.31 mag. Again, the ordinate spans 0.4 mag for each plot.

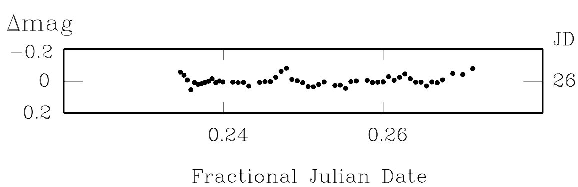

Figure 4. Differential *B*-band light curve of RS Oph from 2006 October 17, normalized to the mean magnitude over the night.

these three nights. Applying these criteria to 10 min periods within each night's data, we detect at least probable flickering for all 10 min periods on six nights, and definite flickering for at least half of all 10 min periods on six nights. Again, despite being conservative estimates, these values are very close to R_{var} for definite flickering. Table 1 shows the mean ratio R_{var} averaged over all 10 min intervals for each night, and also for each night's full data set. The statistical analysis presented here is adequate to demonstrate that significant flickering is detected on time-scales of 10 min to 2 h.

Using equation (3) of Gromadzki et al. (2006), we obtain *V*-band flickering amplitudes (A) in RS Oph ranging from 0.06 to 0.32 mag. Table 1 lists flickering amplitudes derived from both the full data set for each night as well as mean values for 10 min intervals within each night's data.

A decrease in the mean magnitude of RS Oph over the two-week period is depicted in Fig. 5, from which the range in V magnitude detected each night is also apparent. The mean magnitude for each night is given in Table 1.

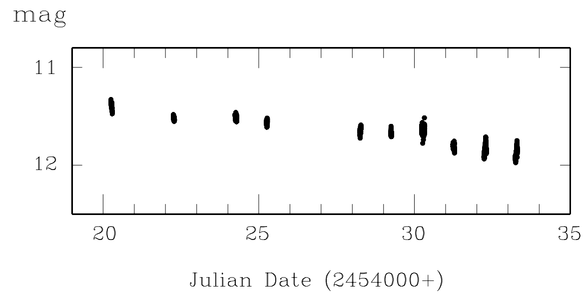

Figure 5. Decline in *V* magnitude of RS Oph plotted for each night over the two-week observational period.

4 DISCUSSION

During observations made between days 241 and 254 post-outburst, we detected aperiodic *V*-band variability in RS Oph, with amplitudes ranging from ∼0.1 to ∼0.3 mag, constituting 'strong flickering' (Sokoloski et al. 2001). Observations made by Zamanov et al. (2006) on day 117 of the 2006 outburst show no variability with amplitude above 0.03 mag. In dwarf novae, optical flickering is attributed to two sources: the turbulent inner regions of the disc and the bright spot, where the stream of matter from the Roche lobe-filling donor star impacts the outer edge of the accretion disc, with inhomogeneities in the flow thought to result in flickering (e.g. Kenyon 1986; Warner 1995). The physical mechanism that causes flickering in symbiotics is not well understood, but is believed to originate from accretion on to a white dwarf (Zamanov & Bruch 1998). Adopting this assumption, these observations are consistent with re-establishment of accretion between days 117 and 241 after the onset of the 2006 outburst. This is the earliest reported detection of flickering subsequent to an outburst in RS Oph.

4.1 Mass transfer rate

Mass transfer from the secondary component is generally attributed to one of two mechanisms: either Roche lobe overflow (RLOF) on to an accretion disc or through direct accretion of matter from the red giant wind on to the white dwarf. Assuming the flickering we observe originates from a re-established accretion disc, we can place a constraint on the mass transfer rate. Sokoloski & Kenyon (2003) relate the time taken to re-establish the disc (the viscous time-scale, t_{visc}) to the inner radius of the disc (R_{I}). This radius can be further related to the rate of mass transfer through the disc (which in this case, we assume to equate to the white dwarf accretion rate, $\dot{M}_{\mathrm{acc}}$) and the dynamical time-scale (t_{dyn}), which is approximately the time-scale of flickering. Re-arranging these equations sourced from Frank, King & Raine (1992), we find:

$$\dot{M}_{\mathrm{acc}} \sim 800(\alpha)^{-8/3}(t_{\mathrm{visc}})^{-10/3}(t_{\mathrm{dyn}})^{25/9}\left(\frac{M_{\mathrm{WD}}}{\mathrm{M}_{\odot}}\right)^{20/9},$$

where $\dot{M}_{\mathrm{acc}}$ is in units of $\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$ and α depends on the state (high or low) of the disc, with $\alpha = 0.03$ in the low state (Warner 1995), which we assume in this case. We take M_{WD} to be 1.35 $\mathrm{M}_{\odot}$ (Hachisu & Kato 2000). As flickering recommenced between days 117 and 241, we have a range of $1.01 \times 10^{7} \leqslant t_{\mathrm{visc}} \leqslant 2.08 \times 10^{7}$ s. The shortest time-scale on which we see flickering is $t_{\mathrm{dyn}} \approx 600$ s. Thus for a low state, we obtain an upper limit of $\dot{M}_{\mathrm{acc}} \leqslant 4.1 \times 10^{-9}$ and a lower limit of $\dot{M}_{\mathrm{acc}} \geqslant 3.7 \times 10^{-10}\,\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$.

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4.2 Mass transfer mechanism

In order to put this into context in terms of the mass transfer mechanism operating in the system, we now consider these values relative to mass transfer rates expected for accretion direct from the red giant wind and via RLOF. A mass accretion ratio, *f*, defined as the ratio of the mass accreting on to the primary $\dot{M}_{\rm acc}$, to the mass-loss rate from the donor companion $\dot{M}_{\rm giant}$, has been calculated by Nagae et al. (2004). They quote $f \leqslant 1$ per cent in a typical wind case, increasing to $f \sim 10$ per cent for RLOF. Studies of the symbiotic star EG And by Vogel (1991) yield a mass-loss rate from the red giant of $10^{-8}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$. Since EG And has a number of similar parameters to RS Oph [M2 red giant secondary, 483 d orbital period (Fekel et al. 2000) cf. ≈460 d in RS Oph (Dobrzycka & Kenyon 1994), similar absolute magnitude (Sokoloski et al. 2001)], we adopt $\dot{M}_{\rm giant} \sim 10^{-8}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$ for RS Oph. Applying the ratios from Nagae et al. (2004) to this mass-loss rate results in accretion rates of $\dot{M}_{\rm acc} \sim 10^{-9}\,{\rm M}_{\odot}{\rm yr}^{-1}$ for RLOF and $\dot{M}_{\rm acc} \leqslant 10^{-10}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$ for direct wind accretion. Thus, our $\dot{M}_{\rm acc}$ limits calculated in Section 4.1 span the range required for direct wind accretion and RLOF at the time accretion resumed.

4.3 Outburst mechanism

Since the outburst mechanism is dependent on the mass transfer rate, we now consider the implications of the rate determined for this early stage of resumed accretion. Yaron et al. (2005) present a grid of outburst characteristics compiled from models of thermonuclear runaway in novae. These data predict that for a system with a mass transfer rate of 10^{-9} to $10^{-10}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$ on to a hot $1.4\,{\rm M}_{\odot}$ white dwarf, we should expect an outburst recurrence period ranging from 200 to over 1000 yr, whereas the time elapsed between observed outbursts in RS Oph averages ∼20 yr. Indeed, translating this model to a slightly lower white dwarf mass more appropriate for RS Oph [i.e. $1.35\,{\rm M}_{\odot}$ from Hachisu & Kato (2000)] produces a further increase in the outburst recurrence interval since the accreted mass required to trigger thermonuclear runaway is higher for a lower mass white dwarf. To allow for discrepancies in the white dwarf mass, basing these calculations on the value of $1.2\,{\rm M}_{\odot}$ determined by Starrfield et al. (1996) results in a lower $\dot{M}_{\rm acc}$, lengthening the recurrence interval still further. From Yaron et al. (2005), a recurrence period of ∼20 yr is achievable only if we have 100 per cent accretion efficiency, that is, $\dot{M}_{\rm acc} = \dot{M}_{\rm giant} = 10^{-8}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$, which far exceeds the findings of, for example, Nagae et al. (2004) (Section 4.2). While our upper limit on the accretion rate approaches $10^{-8}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$, the non-linear relation of the Yaron et al. (2005) model means that the recurrence period remains several times longer than 20 yr for $\dot{M}_{\rm acc} \sim 4 \times 10^{-9}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$ and indeed a factor of 2 greater than the longest interval between observed outbursts in this system.

The accretion luminosity of the system would be most accurately measured at ultraviolet (UV) wavelengths. While observations were made in the UV with *Swift*, none exists prior to day 25 (Goad & Beardmore, private communication). From this point on, the UV tracks the behaviour of the supersoft X-ray emission attributed to fusion on the white dwarf surface (Hachisu, Kato & Luna 2007). The 1985 observations came at a similar point post-outburst. Hence, between outbursts we need to estimate accretion rates by less direct methods. Standard accretion theory predicts that disc luminosity is proportional to the mass transfer rate (Zamanov & Bruch 1998). Thus, the visual quiescent variation of 2.5 mag reported by Oppenheimer & Mattei (1993) implies a factor of 10 variation in mass transfer rate during quiescence. As the visual magnitude during our observations was at the lower end of the quiescent magnitude range this implies that the inter-outburst accretion rate is typically higher than we see here.

Such variations of mass transfer rate are plausible in either the RLOF or wind accretion scenario; either on short-time-scales due to erratic or clumpy mass transfer, or over longer periods, perhaps increasing as the disc becomes better established. Hachisu & Kato (2000), for example, determine a much larger mass accretion rate of $\dot{M} = 1.2 \times 10^{-7}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$ for RS Oph between the outbursts in 1967 and 1985, and brightness variations of up to 3 mag have been observed during periods of quiescence (Rosino 1987). Furthermore, recurrence intervals in this object vary from 9 to 35 yr. Orbital eccentricity may have a particularly marked effect on the rate of mass transferred by direct wind accretion, as the white dwarf trajectory would trace a route through varying densities of the red giant wind. Indeed, the eccentricity in the system is completely unconstrained; Dobrzycka, Kenyon & Milone (1996) quote $e = 0.25 \pm 0.70$, when modelled using the giant component and $e = 0.40 \pm 1.40$ using the white dwarf. Another factor not accounted for in the models that could potentially cause inconsistencies in the nova recurrence interval is that of residual heating of the white dwarf following an outburst, lowering the accreted mass required to trigger a subsequent outburst. Further, work is needed to fully verify the outburst mechanism in this and similar systems.

5 CONCLUSIONS

(i) Statistically significant flickering is detected in RS Oph on days 241–254 of the 2006 outburst, consistent with the re-establishment of accretion between days 117 and 241 after outburst.

(ii) Over the two-week period of observations, the mean *V* magnitude decreases by ∼0.5 mag from 11.4 to 11.9 mag.

(iii) Calculated limits on the white dwarf accretion rate of $4 \times 10^{-10} \lesssim \dot{M}_{\rm acc} \lesssim 4 \times 10^{-9}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$ span the range required for both direct wind accretion and RLOF mechanisms. We therefore find no conclusive evidence favouring one accretion mechanism over the other in RS Oph.

(iv) Current models are not sufficiently complete to confidently determine the accretion and the outburst mechanisms in RS Oph.

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