RS Ophiuchi: Thermonuclear Explosion or Disc Instability?

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ABSTRACT
Sokoloski et al (2008) have recently reported evidence that the recurrent nova RS Ophiuchi produced a pair of highly collimated radio jets within days of its 2006 outburst. This suggests that an accretion disc must be present during the outburst. However in the standard picture of recurrent novae as thermonuclear events, any such disc must be expelled from the white dwarf vicinity, as the nuclear energy yield greatly exceeds its binding energy. We suggest instead that the outbursts of RS Oph are thermal–viscous instabilities in a disc irradiated by the central accreting white dwarf. The distinctive feature of RS Oph is the very large size of its accretion disc. Given this, it fits naturally into a consistent picture of systems with unstable accretion discs. This picture explains the presence and speed of the jets, the brightness and duration of the outburst, and its rise time and linear decay, as well as the faintness of the quiescence. By contrast, the hitherto standard picture of recurrent thermonuclear explosions has a number of severe difficulties. These include the presence of jets, the faintness of quiescence, and the fact that the accretion disc must be unstable unless it is far smaller than any reasonable estimate.

Key words: accretion, accretion discs – binaries: close – novae, cataclysmic variables – stars: dwarf novae

1 INTRODUCTION
Sokoloski et al (2008) have presented evidence that within days of its 2006 outburst the recurrent nova RS Ophiuchi produced a pair of highly collimated ('half-opening angles of a just few degrees') and high velocity ($v \sim 5000 \text{ km s}^{-1}$) jets. Taylor et al. (1989) made similar deductions after the previous (1985) outburst. We argue here that this provides compelling evidence about the cause of the outburst in this object.

The source of the energy driving the outbursts in recurrent novae has been under discussion for some time (e.g. Livio, Truran & Webbink, 1986). There are two basic possibilities: either the outburst is caused by a nuclear explosion on the surface of a white dwarf, akin to a classical nova explosion, but smaller in scale, or the outburst is powered by accretion energy released by a change in the accretion rate on to the central white dwarf, akin to nova outbursts but larger in scale, and similar in nature to the transient X-ray binaries (which differ in having a central neutron star or black hole as the accretor).

It is, however, difficult to see how a nuclear–powered explosion on the surface of an accreting white dwarf could give rise to such well–collimated jets. In general one would expect nuclear burning in the hydrogen–rich surface shell to be quasi–spherically symmetric. The nuclear energy yield from the hydrogen–rich matter considerably exceeds its binding energy at the surface of a white dwarf. In a nuclear–powered nova, the mass of explosively burning material is comparable to that accreted since the last outburst. The mass in the central regions of any disc must be much smaller than this, and is even less gravitationally bound than the matter on the white dwarf surface. Thus the mass in such a disc does not have enough inertia to provide strong collimation of the flow. This point is underlined by the lack of any strongly collimated flows to be seen in ejecta from classical novae (Slavin et al., 1995; Gill & O'Brien, 1998). One only sees slight asymmetries in the shells of material expelled by the nova explosion, presumably caused by the presence of a close binary companion, and lumpiness in the shells (presumably caused by instabilities in the ejection process).

In contrast, the jets seen in RS Oph are high velocity and strongly collimated. As such they are strongly reminiscent of jets seen in other astronomical objects such as radio galaxies, active galactic nuclei (AGN), microquasars, some binary X-ray sources and young stellar objects. These jets all have the following in common (Pringle, 1993; Livio, 1999, 2000; Price, Pringle & King, 2003): the source of the jet has accretion occurring through a disc; the jet velocities are comparable to, or slightly higher than, the escape velocity from the central accreting object; and about 10 per cent of the accreting material is being ejected in the jet. There is also
a suggestion that the collimation of such jets require a large ratio of inner to outer disc radii. It is immediately clear that the jets seen in RS Oph fall precisely into this category.

We therefore argue here that we should abandon the view that the recurrent outbursts of RS Oph are nuclear–powered. We propose instead that the outbursts are driven by gravitational accretion energy, so that the system is actually a dwarf nova with unusual properties which all stem from the fact that its accretion disc is far larger in size than in normal dwarf novae. This property leads to unusually bright, long–lasting outbursts, in which irradiation of the disc by the central source probably plays a role, and similarly long quiescences. Many such outbursts are observed to have jets.

In the rest of this paper we first show that a dwarf nova origin offers a reasonable explanation of the outbursts of RS Oph, and then examine the evidence for a thermonuclear origin. Section 4 is a discussion.

2 RS OPH AS AN IRRADIATED DWARF NOVA

The orbital period of RS Oph is 453.5 days (Brandi et al., 2009; Fekel et al., 2000), implying a binary separation \( a \sim 1.4 \) AU. The companion star is a red giant, and the measured period gives its orbital velocity as 30\( M_\odot^{1/3}(1 + M_2/M_1)^{-2/3} \) km s\(^{-1}\) where \( M_1, M_2 \) are the white dwarf and giant masses in \( M_\odot \), and mass transfer stability requires \( M_2 \lesssim M_1 \). (Assuming that the emission wings of the H\( \alpha \) line trace the motion of the white dwarf, Brandi et al. (2009) give \( M_1 = 0.59 \sin^3 i, M_2 = 0.35 \sin^3 i \), with \( i \) the inclination.) Mass transfer could potentially occur either through capture of the red giant wind or Roche lobe overflow. However since the stellar wind velocity \( \sim 20 \) km s\(^{-1}\) (Bode & Kahn, 1985, p. 206) is unlikely to exceed the giant’s orbital velocity the dynamics of the mass transfer must be similar to Roche lobe overflow even if the giant’s photosphere does not fill this lobe. The system thus has an accretion disc with outer radius \( \sim 70\% \) of the white dwarf Roche lobe, hence size \( \sim 0.5a \sim \) few \( \times 10^{17} \) cm. Unless the outer radius of the accretion disc is far smaller than this estimate, i.e. \( \sim 4 \times 10^{10} \) cm \( \sim 2 \times 10^{-3}a \), the gas there must be much cooler than the typical temperature \( T_H \sim 6500 \) K for hydrogen ionization, implying that the system must undergo disc instabilities.

A disc instability at radius \( R \sim 10^{12}R_{12} \) cm has characteristic viscous timescale \( t_{\text{visc}} \sim R^2/\nu \) with \( \nu \) the kinematic viscosity. We adopt the standard parametrization \( \nu = \alpha c_s H \), where \( c_s \) is the local sound speed and \( H \) the disc scale–height, with \( \alpha \) a dimensionless parameter. In a thin, fully–ionized disc, a wide range of observations give a typical value \( \alpha \sim 0.1 \)–0.4 (King et al., 2007). Accordingly for the hot, outburst state of the disc in RS Oph we take the viscosity coefficient as \( \alpha_{\text{hot}} = 0.1 \alpha_{\text{c}} \). Using eqs (5.49) of Frank et al., 2002, this gives

\[
t_{\text{visc}} = 150\alpha_{0.1}^{-0.8} R_{12}^{1.25} M_{21}^{-0.3} \text{ days}
\]

where \( R_{12} \) is the disc radius in units of \( 10^{12} \) cm, and \( M_{21} \) the peak outburst accretion rate in units of \( 10^{21} \) g s\(^{-1}\). Immediately before the outburst begins, a significant part of the disc must reach the maximum surface density \( \Sigma_{\text{max}}(R) \) for a range of disc radii \( R \), and one could in principle estimate the unstable disc mass by integrating this quantity. But \( \Sigma_{\text{max}}(R) \) depends on the cool–state disc viscosity, which is essentially unknown, so we take instead \( \Sigma(R) = f \Sigma_{\text{min}} = 8.25 \times 10^{3}\frac{M_{12}^{0.35} \alpha_{h}^{-0.8}}{g \text{ cm}^{-2}} \). Here \( \Sigma_{\text{min}} \) is the minimum surface density attained at the end of the outburst, so that \( f > 1 \) (cf eqn (5.84) of Frank et al., 2002). Integrating this over the disc surface we can estimate the total disc mass \( M_d \) before outburst. We approximate the local peak accretion rate as \( M \sim 2M_\odot/t_{\text{visc}} \), as appropriate for an exponential or linear viscous decay (see below) and using (6) above we can now solve for \( M \) and \( t_{\text{visc}} \) as functions of \( R_{12} \), i.e.

\[
t_{\text{visc}} = 127\alpha_{0.1}^{-0.8} R_{12}^{0.48} M_{1}^{0.15} \text{ days}
\]

and

\[
M_{\text{peak}} = 2 \times 10^{21} R_{12}^{5.7} M_{1}^{-0.5} f^{1.43} \text{ g s}^{-1}
\]

with the consequence

\[
M_{\text{peak}} = 5.5 \times 10^{20} t_{100}^{0.43} \alpha_{0.1}^{4.3} M_{1}^{-1/3} f^{1.43} \text{ g s}^{-1}
\]

where \( t_{100} \) is \( t_{\text{visc}} \) in units of 100 days.

Before using these relations for RS Oph, we note that they give very reasonable estimates for known cases of viscous decays if we take the parameter \( f = \Sigma_{\text{max}}/\Sigma_{\text{min}} \sim 1 \), as indeed suggested by numerical modelling of disc instabilities (see Lasota, 2001) for a review).

Thus for a superoutburst of an SU UMa system we take \( M_1 = 0.7, R_{12} = 2.5 \times 10^{-2} \) and find a peak outburst accretion rate \( 2 \times 10^{17} f^{1.43} \) g s\(^{-1}\) (accretion luminosity \( L \sim 10^{34} f^{1.43} \) erg s\(^{-1}\) ) and a decay timescale of \( \sim 14 \) days.

For a neutron–star X–ray transient we take \( R_{12} = 1.0, M_1 = 1.4 \) and find a slightly super–Eddington luminosity \( L \sim 5 \times 10^{38} f^{1.43} \) erg s\(^{-1}\) with \( t_{\text{visc}} \sim 42 \) days.

Both estimates, and others that one can make for e.g. black–hole accretors in transients, agree well with observed systems, so we now apply eqns (6) to RS Oph.

2.1 Application to RS Oph

For RS Oph we take \( R_{12} \simeq 1, M_1 \simeq 1 \) and find a peak accretion rate

\[
M_{\text{peak}} \simeq 1.7 \times 10^{21} f^{1.43} \text{ g s}^{-1} = 2.5 \times 10^{-5} M_\odot \text{ yr}^{-1},
\]

with an outburst timescale

\[
t_{\text{visc}} \simeq 128\alpha_{0.1}^{-0.8} \text{ days}
\]

The accretion rate (6) is somewhat super–Eddington (for gravitational energy release), formally giving a luminosity \( G M_{\text{peak}}/R = 4.6 \times 10^{38} \) erg s\(^{-1}\) for accretion on to a 1M_\odot white dwarf, so that \( M_{\text{peak}} \simeq 3M_{\text{Edd}} \). In line with expectations from other super–Eddington accretors such as ultraluminous X–ray sources we anticipate strong outflow from the inner parts of the accretion disc, leading to an accretion luminosity \( L \simeq L_{\text{Edd}}[1 + \ln(M_{\text{peak}}/M_{\text{Edd}})] \simeq 2L_{\text{Edd}} \) (cf Shakura & Sunyaev, 1973; Begelman et al., 2006, Poutanen et al., 2007). At this value \( M_{\text{peak}}/M_{\text{Edd}} \sim 3 \) the emission is almost isotropic (at higher values of this ratio it is collimated towards the disc axis). The system should thus have a luminosity of \( \sim 2L_{\text{Edd}} \) unless viewed at very high inclination. This agrees with observations of RS Oph, as does the outburst duration implied by (6).
The rise of RS Oph to maximum was very rapid ($\lesssim 1$ day). This follows from the dwarf nova picture given here also. To brighten from an accretion luminosity of $10^{37}$ erg s$^{-1}$ to $10^{38}$ erg s$^{-1}$ requires the disc instability heating front to move from disc radius $R_d \sim 10^{10}$ cm to the white dwarf radius, which is about 10 times smaller. Eqn (51) of Lasota (2001) shows that the disc instability must be of ‘inside–out’ type, as the opposite would require a mass transfer rate greater than about $4 \times 10^{30}$ g s$^{-1}$, i.e. comparable with the outburst accretion rate. For such outbursts the front moves with a velocity $\sim c_h c_s$, so the rise time is

$$t_{\text{rise}} \gtrsim \frac{R_d}{c_h c_s}. \quad (7)$$

Using the disc central temperature given by Frank et al., 2002 (eqn 5.49) to estimate $c_s$ we find $t_{\text{rise}} \gtrsim 3$ hours.

Thus far the dwarf nova model gives a consistent representation of the outburst of RS Oph. However we need one modification of the usual picture. A normal dwarf nova outburst would end not after a viscous time, but after a local thermal time, which is considerably shorter. The crucial difference in RS Oph is the very large size of the accretion disc. This means that irradiation by the central source (temperature $\propto R^{-1/2}$) must dominate local viscous energy release (temperature $\propto R^{-3/4}$) at large disc radii, where most of the disc mass is. The outburst then resembles those of soft X–ray transients: the disc is trapped in the hot outburst state un- 

differently in RS Oph is the very large size of the accretion disc. For such outbursts the front moves with a velocity $\lesssim c_h c_s$, so the rise time is

$$T_{\text{rise}} \lesssim \frac{L_c g}{4\pi R^2 \sigma} \left(\frac{H}{R}\right) \quad (8)$$

where $\sigma$ is the Stefan–Boltzmann constant, $g$ is a geometric factor of order 0.2, and $H/R \sim 0.04$ is the disc aspect ratio. This gives an irradiation temperature of order

$$T_{\text{irr}} \simeq 6700 \left(\frac{L_c}{L_{\text{Edd}} R_{12}^2}\right)^{1/4} \text{K} \quad (9)$$

that is, the central accreting white dwarf keeps the disc self–consistently in the hot state ($T_{\text{irr}} > T_H$) out to a radius $R_h \sim 10^{12}$ cm at the start of the outburst. In this case the outburst must evolve on the local hot–state viscous time, and decay exponentially or linearly in time depending on whether irradiation keeps the whole disc in the hot state or not (King & Ritter, 1998). As $R_h$ is smaller than the full disc outer radius, the outburst decay should be (bolometrically) linear over a viscous timescale. This is consistent with observation (Page et al., 2008, Fig.1) between days 50 to 100.

Between outbursts we expect the disc to refill, with little or no accretion on to the white dwarf. This offers a natural explanation for the faintness of the system between outbursts, in particular in X–rays (Mukai 2009). We conclude that the main features of the outbursts of RS Oph are successfully explained in terms of an instability in a disc irradiated by the central accreting white dwarf.

### 3 RS OPH AS A RECURRENT THERMONUCLEAR SOURCE

We have suggested above that the outburst behaviour of RS Oph is explicable in terms of instabilities in an irradiated disc. Until now the usual interpretation of RS Oph and other recurrent novae is that matter accumulates on the surface of the white dwarf until it reaches the base pressure $P_{\text{crit}} \sim 2 \times 10^{19}$ dyne cm$^{-2}$ required to ignite as a runaway thermonuclear event. We note that the presence of processed material in the outbursts is not per se proof of nuclear burning in the outburst, since the companion star is evolved. Thus any material transferred to the white dwarf and subsequently expelled in an accretion–driven outburst came originally from the convective envelope of the red giant, where it mixed with products of the nuclear–burning shell around the degenerate core. Its composition therefore does not differ greatly from that of matter partially burnt and ejected from the white dwarf surface in a classical nova.

This picture has several difficulties, which we list below.

1. The presence of jets requires an accretion disc, and is very hard to reconcile with a thermonuclear model, as noted in the Introduction. The nuclear energy yield from burning hydrogen–rich matter considerably exceeds its gravitational binding energy at the surface of a white dwarf. Hence a thermonuclear explosion would inevitably blow away the inner parts of any accretion disc.

2. Even assuming a mass $M_1$ close to the Chandrasekhar limit, the white dwarf has to accrete at a rate $\dot{M} = P_{\text{crit}} R_1^2 / G M_1 t_{\text{eq}} \gtrsim 10^{-8} M_\odot$ yr$^{-1}$ in order to accumulate enough mass to ignite the outbursts (here $R_1$ is the white dwarf radius, and $t_{\text{eq}} \sim 20$ yr is the duration of quiescence). But the accretion rate $\dot{M} \gtrsim 10^{-8} M_\odot$ yr$^{-1}$ is hard to reconcile with the lack of X–rays observed from RS Oph in quiescence. Mukai (2009) considers various possible ways out of this conclusion, including combinations of very high intrinsic absorption columns and totally optically thick boundary layers, and concludes that none are convincing. In particular, CVs with boundary layer emission always in practice have a surface layer optically thin enough to produce hard X–rays (Patterson & Raymond, 1985), i.e. an optically thin region where accretion energy is released.

3. The very wide binary orbit of RS Oph suggests that its disc is likely to be unstable, and thus reduce central accretion severely below the value $\dot{M} \gtrsim 10^{-8} M_\odot$ yr$^{-1}$ required for the thermonuclear model. To avoid this the outer disc radius must be smaller than $\sim 2 \times 10^{12}$a, where a is the binary separation. This is ruled out if the giant fills its Roche lobe, and very unlikely even if mass transfer is via stellar wind capture, since the wind speed is rather less than the orbital velocity of the giant companion.

We note finally that the dwarf nova–type outbursts considered in Section 2 imply a mean white dwarf accretion rate $\dot{M}_d \lesssim 7 \times 10^{-8} M_\odot$ yr$^{-1}$ if they recur at the current rate of one per $\sim 20$ yr (note that mass loss during the outburst makes this an upper limit). With a non–extreme white dwarf mass one might then speculate on a thermonuclear nova occurring after a few outbursts. However the ultimate source of mass is not the disc, but the companion star. Unless this transfers mass at a rate $\gtrsim \dot{M}_d$ the disc will run out of mass and the outbursts will recur more slowly. This is another way of saying that (as always) the nova recurrence time is
\[ \sim \frac{\Delta M}{(-\dot{M}_2)}, \] where \( \Delta M \) is the mass that has to accumulate on the white dwarf surface. For mass transfer on the nuclear timescale of a low-mass giant (as here), the likely rate \( -\dot{M}_2 \) is less than \( \dot{M}_0 \) by factors \( \sim 3 \) (cf Webbink, Rappaport & Savonije, 1983). This suggests a ‘supercycle’ of outbursts and a nova recurrence time \( \gtrsim 10^3 \) yr. This is short compared with most CVs simply because \( -\dot{M}_2 \) is much larger here.

4 DISCUSSION

The distinctive feature of RS Oph is the very large size of its accretion disc. Given this, it fits naturally into a consistent picture of systems with unstable accretion discs. This picture explains the presence and speed of the jets, the brightness and duration of the outburst, and its rise time and linear decay, as well as the faintness of the quiescence. We would expect this general picture to apply to other long-period systems, e.g. T CrB.

By contrast, the hitherto standard picture of recurrent thermonuclear explosions has a number of severe difficulties. These include the presence of jets, the faintness of quiescence, and the fact the accretion disc must be unstable unless it is far smaller than any reasonable estimate.

A simple observational test of the thermonuclear picture would be provided by a dynamical mass determination of the white dwarf mass. A thermonuclear origin for the outbursts requires a mass extremely close to the Chandrasekhar value \( \sim 1.4M_\odot \).

REFERENCES

Begelman M. C., King A. R., Pringle J. E., 2006, MNRAS, 370, 399
Brandon, E., Quiroga, C., Mikolajewska, J., Ferrer, O. E., & Garcia, L. G. 2009, arXiv:0902.2177
Bode, M. F., & Kahn, F. D., 1985, MNRAS, 217, 205
Fekel F. C., Joyce R. R., Hinkle K. H., Skrutskie M. F., 2000, AJ, 119, 1375
Frank J., King A., Raine D. J., 2002, Accretion Power in Astrophysics, 3rd Edition, Cambridge University Press
Gill C. D., O'Brien T. J., 1998, MNRAS, 300, 221
King A. R., Pringle J. E., Livio M., 2007, MNRAS, 376, 1740
King A. R., Ritter H., 1998, MNRAS, 293, L42
Lasota J.-P., 2001, NewAR, 45, 449
Livio, M., 1999, Phys. Rep. 311, 225.
Livio, M., 2000, in 'Cosmic Explosions', AIP Conference Proceedings 522, eds. S S Holt, W W Zhang (Melville, NY: AIP), p. 275
Livio M., Truran J. W., Webbink R. F., 1986, ApJ, 308, 736
Mukai, K., 2009, in ASP conference proceedings Volume 401 "RS Ophiuchi (2006) and the recurrent nova phenomenon".p. 84 (arXiv:0803.2912)
Page, K.L., Osborne, Beardmore, A.P., Goad, M.R., Wynn., G.A., Bode, M.F., O’Brien, T.J., 2008, in ASP conference proceedings Volume 401 "RS Ophiuchi (2006) and the recurrent nova phenomenon", p. 283
Price, D J., Pringle, J E., King, A R., 2003, MNRAS, 339, 1223
Pringle, J.E., 1993, in 'Astrophysical Jets', eds. D Burgarella, M Livio, C O’Dea, Cambridge University Press, p. 1.
Poutanen J., Lipunova G., Fabrika S., Butkevich A. G., Abolmasov P., 2007, MNRAS, 377, 1187
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Slavin A. J., O’Brien T. J., Dunlop J. S., 1995, MNRAS, 276, 353