

# The recurrent nova RS Oph: A possible scenario for type Ia supernovae

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## Abstract

The recurrent nova RS Oph experienced an outburst in 2006, 21 years after its previous explosion in 1985, as expected. It was observed at almost all wavelengths, and important information about its properties is still being extracted. We present theoretical models of the explosion of this fascinating object, which indicate that the mass of the accreting white dwarf should be very close to the Chandrasekhar mass, to allow for such a short recurrence period. In addition, since models suggest that this nova ejects less mass than it accretes, it is an excellent candidate for a thermonuclear supernova explosion, in about  $10^5 - 10^7$  years from now. We also analyze the emission of soft gamma-rays by RS Oph detected with the BAT instrument onboard Swift, and with the PCA onboard RXTE. We rule out that this emission has its origin in radioactive decays in the expanding nova envelope.

*Key words:* binaries: close, binaries: symbiotic, novae, cataclysmic variables, stars: individual (RS Oph), supernovae: general, nucleosynthesis, gamma-ray astronomy

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## 1 Introduction

Recurrent novae are defined as systems with more than one recorded nova outburst. There are few members of the recurrent novae subclass: just 10 (see Anupama & Mikolajewska (1999) and review by Mikolajewska (2008)), divided in two groups according to their orbital periods. RS Oph belongs to the long period group, with  $P_{\text{orb}} = 456$  days (Fekel et al., 2000), which are

interpreted as interacting binaries where a hot white dwarf accretes mass from a giant secondary; these recurrent novae are a subclass of symbiotic binaries. In contrast, classical novae occur in cataclysmic variables, a different type of binary system where a white dwarf accretes mass from a main sequence companion, overflowing its Roche lobe; typical periods of cataclysmic variables are about a few hours.

RS Oph has undergone various recorded outbursts (1898, 1933, 1958, 1967, 1985 and 2006, and two additional possible outbursts in 1907 and 1945). In the two last outbursts, a lot of observational data was gathered. The recent outburst in 2006 offered the opportunity to observe RS Oph at practically all wavelengths, radio, IR, optical, X-rays and soft gamma-rays. However, the very important UV range was missing, since there was not a satellite “equivalent” to IUE flying in 2006. It was a pity, since IUE made very important observations in the previous RS Oph eruption in 1985 (Shore et al., 1996), which could not be repeated in 2006. On the other hand, current space missions like Spitzer, RXTE, XMM-Newton, Chandra and Swift have provided a wealth of IR and X-rays data, of much better quality than what could be obtained at such energy ranges in the previous outburst. All in all, there is now an impressive data set; its interpretation is a real challenge for theorists and it has provided already many exciting results.

It is worth noting that there is not yet a self consistent model of the RS Oph outburst itself, since it is not straightforward to find a set of initial conditions leading to a thermonuclear runaway (TNR) with a recurrence period as short as 21 years; classical novae recurrence periods are much longer ( $\geq 10^4 - 10^5$  years), well in agreement with the expected time to reach outburst conditions with typical accretion rates and initial white dwarf masses in cataclysmic variables. The only known way to reconcile a short interoutburst period -about some decades- with a TNR (i.e., explosive hydrogen burning in degenerate conditions on top of the white dwarf), is that a very massive white dwarf, close to the Chandrasekhar limit, accretes with a large mass accretion rate. This fact gives an additional interest to RS Oph and its relatives, since they are potential progenitors of thermonuclear -or type Ia- supernovae, in a relatively short time, if the white dwarf grows in mass in each nova eruption. Our evolutionary models indicate that ejected mass is smaller than accreted mass, so confirming that possibility.

In this paper we present our recent attempts to model the basic properties of the RS Oph recurrent nova outburst, with special emphasis on the ratio of ejected to accreted mass, the ejecta chemical composition and the potential gamma-ray emission. The role played by the initial conditions of the white dwarf is underlined. We also discuss the impossibility to explain the Swift/BAT hard X-soft gamma-rays detections as related with the continuum gamma-ray emission coming from electron-positron annihilation in the

expanding ejecta.

## 2 Main observational properties

The last eruption of RS Oph was recorded on 2006 February 12.83 UT, reaching magnitude 4.4 (Narumi et al., 2006). Observations at other wavelengths have provided important data. For instance, radio observations yielded a new detection (not obtained in the previous outburst) of early emission at low radio frequencies, clearly of nonthermal origin (Kantharia et al., 2007), and high resolution VLBA images, clearly showing an asymmetric expanding shock wave (O’Brien et al., 2006). Early X-ray observations with RXTE (Sokoloski et al., 2006) and Swift/BAT (Bode et al., 2006) showed hard X-ray emission (up to 50 keV), a clear indicator of the blast wave from RS Oph, i.e. an outward propagating shock wave consequence of the interaction between the expanding ejecta and the red giant wind (the latter much denser than typical circumstellar material in classical novae). Additional data about the early evolution came from IR observations, which also showed the temporal evolution of the shock velocity (Das, Banerjee & Ashok, 2006; Evans et al., 2007). There is a difference in the shock velocities deduced from the X-ray and IR data, which has been shown to indicate efficient particle acceleration; nonlinear diffusive shock acceleration of cosmic rays also explains the deceleration of the blast wave in RS Oph, which occurred faster than predicted by the standard adiabatic shock wave model (Tatischeff & Hernanz, 2007). IR observations also provide an estimate of the ejected mass:  $\sim 3 \times 10^{-6} M_{\odot}$  (Das, Banerjee & Ashok, 2006). Another important set of observations in X-rays (with Swift/XRT, XMM-Newton and Chandra) revealed highly variable soft X-ray emission at about 30 days post outburst, and lasting for about 60 days, with high temporal variability (Bode et al., 2006; Ness et al., 2007; Nelson et al., 2008). The short duration of the supersoft X-ray phase points again to a very massive white dwarf in RS Oph (Hachisu, Kato & Luna, 2007). This supersoft X-ray emission results from residual hydrogen burning on top of the white dwarf.

It is important to know that overabundances of lithium have been found in RS Oph in quiescence, and also in another recurrent nova, T CrB, sharing its basic properties with RS Oph (Wallerstein et al., 2008).

## 3 Models

The model for classical novae explosions is based on the thermonuclear runaway ensuing hydrogen degenerate burning, on top of an accreting white dwarf, which drives mass ejection at large velocities (hundreds to thousands of km/s).

For typical initial masses and luminosities of the white dwarf, and mass accretion rates from the secondaries, there is an explosion every  $10^4 - 10^5$  years. Some kind of mixing between the accreted matter and the underlying white dwarf should be invoked to explain the large enhancements above solar values of CNO nuclei, and also of neon, found in the ejecta of many novae (a list of abundances in novae ejecta can be found in Gehrz et al. (1998)). However, no large overabundances of metals were found in RS Oph (Shore et al., 1996), so that not much mixing is expected to occur. The main difficulty with the “standard” TNR scenario for RS Oph is the short recurrence period,  $P_{\text{rec}} = 21$  years. Both short  $P_{\text{rec}}$  and lack of overabundances above solar in the ejecta point to fast evolution, only attainable with some particular combinations of large white dwarf mass and accretion rate. A first set of nova models on white dwarfs with  $M=1.38 M_{\odot}$  were computed by Starrfield, Sparks & Truran (1985). At nearly the same epoch, an alternative scenario for RS Oph outburst was invoked (Livio, Truran & Webbink, 1986), casting doubts on the TNR model and assuming a main sequence companion instead of a giant. However, it is nowadays accepted that the companion of the white dwarf in RS Oph is a red giant and that a TNR is responsible for its outburst. One observational fact that proves this scenario is the residual steady H-burning revealed by the supersoft X-ray emission detected  $\sim 30$  days after outburst. Other arguments come from the shock wave revealed both in X-rays, IR and radio.

We reanalyse here the TNR model for RS Oph, by means of the hydrodynamic code described in José & Hernanz (1998), which follows the evolution of the accreting white dwarf from the accretion phase up to mass ejection, with complete nucleosynthesis included, and updated nuclear reaction rates. The initial conditions are very relevant for the ensuing properties of the explosion. An initial mass always larger than  $1.2 M_{\odot}$  has been adopted, with a range of mass accretion rates and white dwarf luminosities. No mixing of any kind between the accreted mass (assumed to have solar composition) and the white dwarf core has been adopted. The main issue is the initial white dwarf luminosity; according to Anupama & Mikolajewska (1999), white dwarfs in symbiotic stars are quite luminous, as a consequence of steady H-burning on their surface. However, such high luminosities do not mean that the whole white dwarf core is very hot, but just its outer envelope. Therefore, once the purely symbiotic phase ends, a central core temperature-luminosity relation is again valid, and relatively low luminosities, such as those required to power a TNR, are possible.

A search for appropriate initial conditions leading to short recurrence periods is the first step to model RS Oph. The recurrence period can be written as  $P_{\text{rec}} = \Delta M_{\text{acc}} / \dot{M} = 21$  years, where  $\Delta M_{\text{acc}}$  is the accreted mass on top of the white dwarf required to power the outburst through a TNR and  $\dot{M}$  is the mass accretion rate. The question is which combinations of the initial white dwarf mass,  $M_{\text{wd}}^{\text{ini}}$ ,  $\dot{M}$  and the initial luminosity,  $L_{\text{wd}}^{\text{ini}}$ , lead to a nova outburst

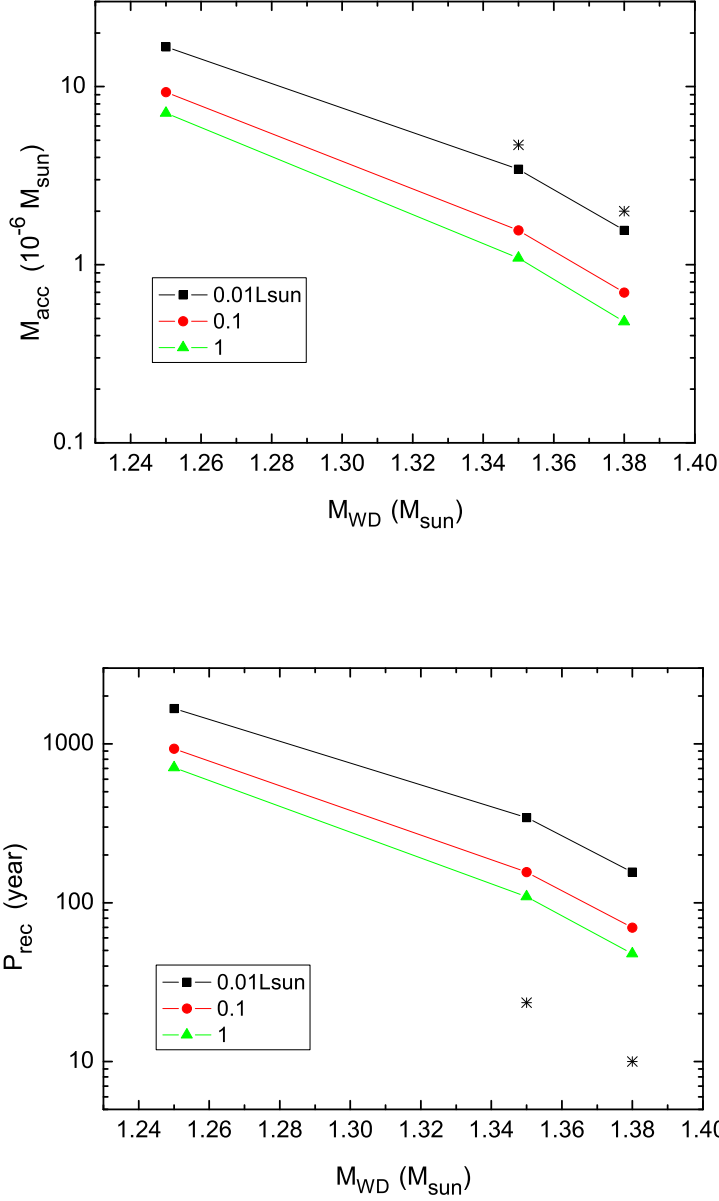


Fig. 1. Upper panel: accreted masses required to reach hydrogen ignition conditions and to power a TNR. Lower panel: recurrence periods for the same set of initial conditions as in the upper panel. Asterisks denote the values obtained for  $\dot{M} = 2 \times 10^{-7} M_{\odot}/\text{year}$  and  $L_{\text{wd}}^{\text{ini}} = 10^{-2} L_{\odot}$ .

with such a short period of 21 years. We have adopted a range of  $L_{\text{wd}}^{\text{ini}}$  between  $10^{-2}$  and  $1 L_{\odot}$ , and two values for  $\dot{M}$  ( $2 \times 10^{-7}$  and  $10^{-8} M_{\odot}/\text{year}$ ). The initial white dwarf mass ranges from 1.25 to 1.38  $M_{\odot}$ . The chemical composition of the white dwarf should be ONe (and not CO) according to standard stellar evolution (see for instance Ritossa, García-Berro & Iben (1996)).

We show in Figure 1 (upper panel) the accreted masses needed to reach hydrogen ignition conditions versus the white dwarf initial mass, for various luminosities and  $\dot{M} = 10^{-8}M_{\odot}/\text{year}$ . We also include the results for  $\dot{M} = 2 \times 10^{-7}M_{\odot}/\text{year}$  and  $L_{\text{wd}}^{\text{ini}} = 10^{-2}L_{\odot}$ . The corresponding recurrence periods are shown in the lower panel of the same figure. One sees at first glance that the critical accreted mass does not depend only on  $M_{\text{wd}}^{\text{ini}}$ , as some basic approximate formula indicate (since they only require that some pressure at the base of the accreted envelope -about  $10^{21-22}$  dyn/cm<sup>2</sup>- is reached to power degenerate H-ignition). As expected, an increase in the initial luminosity reduces the accreted mass needed to power the TNR and thus the recurrence period. Another result is that the decrease in accreted mass and recurrence period is steeper as the initial white dwarf mass approaches the Chandrasekhar limit, since the star becomes easier to destabilize. The main issue is that recurrence periods as short as 21 years are really hard to obtain; only masses larger than  $\sim 1.35M_{\odot}$  and accretion rates about  $10^{-7}M_{\odot}/\text{year}$  can provide them. It is worth noting that the initial luminosity should be reasonably low,  $L_{\text{wd}}^{\text{ini}} = 10^{-2}L_{\odot}$ , to guarantee a TNR. Another possibility is a smaller accretion rate,  $10^{-8}M_{\odot}/\text{year}$ , with larger  $L$ ,  $1 L_{\odot}$ , but the explosion is then less powerful and marginally compatible with observations.

The high accretion rates required agree with some recent predictions from 3D simulations, yielding a red giant mass loss rate of about  $10^{-7}M_{\odot}/\text{year}$  and an accretion rate of about 10% this value, i.e.  $10^{-8}M_{\odot}/\text{year}$  (Walder, Folini & Shore, 2008). It is worth mentioning, however, that observations by Worters et al. (2007) have detected the resumption of optical flickering in RS Oph, indicating that mass accretion had been reestablished, with deduced accretion rates spanning the range between  $10^{-10}$  and  $10^{-9}M_{\odot}/\text{year}$ , depending on the mechanism of accretion (either wind accretion or Roche lobe overflow); with such small accretion rates, recurrence periods would be larger than 21 years by orders of magnitude (José & Hernanz, 1998).

In Table 1 we show some properties of the explosion for the most interesting cases. The models with  $M_{\text{wd}}^{\text{ini}}=1.35$  and  $1.38 M_{\odot}$ ,  $\dot{M} = 2 \times 10^{-7}M_{\odot}/\text{year}$ ,  $L_{\text{wd}}^{\text{ini}} = 10^{-2}L_{\odot}$  illustrate the effect of the initial white dwarf mass: a slight increase in initial mass from 1.35 to 1.38  $M_{\odot}$  reduces the recurrence period by more than a factor of 2 (from 24 to 10 years). The properties of two additional models, with  $\dot{M} = 10^{-8}M_{\odot}/\text{year}$  and two initial luminosities -  $L_{\text{wd}}^{\text{ini}} = 10^{-2}$  and  $1 L_{\odot}$  - are also displayed, to illustrate the effect of the initial white dwarf luminosity and of the mass accretion rate. A decrease in the accretion rate by a factor of 20 increases the recurrence period by a similar factor (from  $\sim 10$  to  $\sim 160$  years), provided that the initial luminosity is unchanged ( $10^{-2}L_{\odot}$ ). On the other hand, an increase by a factor of 100 in the initial luminosity (from  $10^{-2}$  to  $1 L_{\odot}$ ) just reduces the recurrence period by a factor of 2.7 (from  $\sim 160$  to  $\sim 60$  years), provided that the accretion rate and the initial white dwarf mass remain unchanged ( $1.38 M_{\odot}$  and  $10^{-8}M_{\odot}/\text{year}$ , respectively).

Table 1

Main properties of the RS Oph models: peak temperature, accreted and ejected masses, timescales (accretion, recurrence time), total white dwarf mass increase and time needed to reach  $M_{\text{Chandra}}$ . Units are:  $10^8$  K for T,  $M_{\odot}$  for masses, years for times.

$M_{\text{WD}}$	$T_{\text{peak}}$	$M_{\text{acc}}$	$M_{\text{ej}}$	$t_{\text{acc}}$	$t_{\text{rec}}$	$\Delta M_{\text{wd}}$	$\Delta t_{\text{Chandra}}$
$L_{\text{ini}} = 10^{-2} L_{\odot}$ ; $\dot{M} = 2 \times 10^{-7} M_{\odot}/\text{year}$							
1.35	2.8	4.7E-6	3.0E-6	23.3	24	1.7E-6	6.9E5
1.38	3.1	2.0E-6	1.3E-6	10.0	10.4	0.7E-6	2.9E5
$L_{\text{ini}} = 10^{-2} L_{\odot}$ ; $\dot{M} = 10^{-8} M_{\odot}/\text{year}$							
1.38	3.0	1.6E-6	1.1E-6	156	157	4.1E-7	7.6E6
$L_{\text{ini}} = 1 L_{\odot}$ ; $\dot{M} = 10^{-8} M_{\odot}/\text{year}$							
1.38	2.5	4.8E-7	4.0E-7	47.8	57.6	7.7E-8	1.2E7

Peak temperatures (see again Table 1) range around  $(2 - 3) \times 10^8$  K, which are moderate but similar to those of classical novae; in contrast, the total time elapsed since accretion starts up to ignition is much shorter, as already emphasized. The corresponding accreted and ejected masses are quite small,  $\sim 10^{-6} M_{\odot}$  or even smaller ( $\sim 10^{-7} M_{\odot}$  for the model with large initial luminosity,  $1 L_{\odot}$ ). However, the case with large initial luminosity does not give a very energetic explosion and would not well represent RS Oph (but it is not too bad concerning the recurrence period, 58 years, just a factor of  $\sim 3$  above the observed value). The two models with  $\dot{M} = 2 \times 10^{-7} M_{\odot}/\text{year}$  are thus those that best reproduce RS Oph main observed features. The maximum bolometric luminosities reach  $\sim (3 - 5) \times 10^5 L_{\odot}$ , the average global kinetic energy is about  $10^{44}$  erg, with average velocities of  $(3 - 4) \times 10^3$  km/s, and ejected masses are  $\sim 10^{-6} M_{\odot}$ , which indicate that this nova is a bit less energetic than classical ones, and with a smaller content of radioactive nuclei (as shown below).

An important result is that the accreted masses are larger than the ejected ones, so that the mass of the white dwarf increases:  $M_{\text{acc}} - M_{\text{ejec}}$  ranges between  $0.7$  and  $1.7 \times 10^{-6} M_{\odot}$ , leading to an expected time to reach the Chandrasekhar mass ( $M_{\text{Chandra}} = 1.4 M_{\odot}$ ) ranging between  $3$  and  $7 \times 10^5$  years for the two models with  $\dot{M} = 2 \times 10^{-7} M_{\odot}/\text{year}$ . The other models would need much larger times to reach the Chandrasekhar mass, and thus would not be viable type Ia progenitors.

The nucleosynthesis in our models provides large hydrogen and helium abundances in the ejecta (mass fractions  $\sim 0.6$  and  $\sim 0.4$ , respectively). There is not large overproduction with respect to solar of metals, in agreement with observations, and contrary to what is obtained in general for classical no-

vae. The main reason for such a difference is the lack of initial mixing and the rapid evolution to the runaway. Regarding  ${}^7\text{Li}$ , it is not at all overproduced. The key issue in the synthesis of  ${}^7\text{Li}$  is the amount of  ${}^7\text{Be}$  (which is transformed into  ${}^7\text{Li}$  in the ejecta after an electron capture) that survives the TNR (see Hernanz et al. (1996); José & Hernanz (1998)). At the early stages of the TNR,  ${}^7\text{Be}$  is efficiently destroyed by proton capture reactions, but as soon as enough T is reached (about  $(5 - 7) \times 10^8\text{K}$ ) photodisintegration of  ${}^8\text{B}$  drives a pseudo-equilibrium between  ${}^7\text{Be}$  and  ${}^8\text{B}$ . Hence, the final amount of  ${}^7\text{Li}$  strongly depends on the level of  ${}^7\text{Be}$  destruction prior to this pseudo-equilibrium. The faster the TNR, the shorter to reach the pseudo-equilibrium stage, and hence, the larger the final amount of  ${}^7\text{Li}$ . This explains why CO models lead in general to larger amounts of  ${}^7\text{Li}$  in the ejecta as compared with ONe models (since mixing with the underlying CO WD brings  ${}^{12}\text{C}$  fuel into the envelope which speeds up the TNR dramatically). Also, the increase of strength in explosions hosting massive white dwarfs explains why very massive ONe white dwarfs (close to the Chandrasekhar mass) eject larger amounts of  ${}^7\text{Li}$  than not so massive ONe white dwarfs, but never reaching solar values or larger. Thus, the Li overabundance found in RS Oph in quiescence (Wallerstein et al., 2008) is likely not synthesized during the nova outburst.

There are small amounts of the radioactive nuclei relevant for  $\gamma$ -ray emission ( ${}^{13}\text{N}$ ,  ${}^{18}\text{F}$ ,  ${}^7\text{Be}$  and  ${}^{22}\text{Na}$ , see Gómez-Gomar et al. (1998)), i.e., much smaller yields in mass fraction (and also absolute yields, because of the small ejected masses) than for classical novae. In addition, the envelope becomes transparent to  $\gamma$ -rays later than in normal novae, because of the smaller global kinetic energy. All in all, the expected gamma-ray fluxes are very small. This rules out the interpretation of the observed soft  $\gamma$ -rays from RS Oph, with the BAT instrument on board the Swift satellite (Bode et al., 2006), as due to the decay of radioactive nuclei. Shocks within the ejecta should provide a better explanation of the observed hard X-ray emission (Sokoloski et al., 2006; Bode et al., 2006). In fact, one could know beforehand that Swift/BAT observations of RS Oph can not be interpreted as due to radioactive nuclei decay, by two reasons: the spectral shape and the light curve (Gómez-Gomar et al., 1998; Hernanz, Gómez-Gomar & José, 2002). The shapes of the  $\gamma$ -ray spectra expected from radioactive decay at various epochs are such that there is less emission in the 15-25 keV energy band than in the 25-50 keV band, due to the sharp spectral cutoff at low energies produced by photoelectric absorption. The contrary was observed with Swift/BAT and RXTE, as shown in Figure 1 from Bode et al. (2006). Concerning the  $\gamma$ -ray light curve, our models indicate that the maximum in visual flux occurs later than the maximum in  $\gamma$ -rays (simultaneous to peak temperature), for all types of novae, again in contradiction with the observations with Swift/BAT, where the peak in hard X/soft  $\gamma$ -ray emission occurred after the optical outburst (see Figure 1 from Bode et al. (2006)).



## 4 Discussion and conclusions

Models of the RS Oph explosion should account for its main observed properties, e.g., very short recurrence period (21 years), small ejected mass, roughly solar chemical composition of the ejecta and maximum luminosities and ejecta velocities similar to those of classical novae. Hydrodynamic models of massive (larger than  $\sim 1.35 M_{\odot}$ ) accreting white dwarfs with large accretion rates - ranging from  $\dot{M} = 10^{-8}$  to  $2 \times 10^{-7} M_{\odot}/\text{year}$  - well reproduce these features. But there are still some aspects to be better understood, as the need of initially low white dwarf luminosities, as compared with some observations at quiescence. We want to point out a few important puzzles. First of all, very massive white dwarfs should be made of ONe (if they were born as massive white dwarfs); therefore, they pose a problem as scenarios for type Ia supernovae, because ONe white dwarfs rather collapse to a neutron star than explode, when reaching  $M_{\text{Chandra}}$  (see Gutiérrez, Canal & García-Berro (2005) and references therein). One could envision that the white dwarf was initially born as a CO white dwarf, but then it should have been less massive than  $1.1 M_{\odot}$  and be able to reach  $1.35\text{-}1.38 M_{\odot}$  through successive recurrent nova eruptions. However, this seems unrealistic because models do not reproduce such behaviour. Second, the mass left after the recurrent nova explosion, i.e.,  $M_{\text{acc}} - M_{\text{ejec}}$  (see above) should be compatible with the duration of the super soft X-ray emission phase (around 60 days, see Hachisu, Kato & Luna (2007)). According to our models (Sala & Hernanz, 2005), the remnant envelope mass for a hydrogen mass fraction of 0.6 and mass of the white dwarf larger than  $1.3 M_{\odot}$  should be around  $10^{-7} M_{\odot}$ , and surely smaller than  $10^{-6} M_{\odot}$ . Therefore, the mass of the white dwarf is more plausibly  $1.38$  than  $1.35 M_{\odot}$  (see Table 1). Finally, the hard X/soft  $\gamma$ -rays detected with Swift/BAT and RXTE in the early phases of the explosion could not come from electron-positron annihilation emission (with positrons coming from the decay of the  $\beta^+$ -unstable nuclei  $^{13}\text{N}$ ,  $^{18}\text{F}$  in the ejecta), both because of the tiny amount of radioactive nuclei, the too late appearance of such emission and its spectral shape. Deeper studies of both the thermonuclear runaway phase and the interaction between the ejecta and the dense stellar wind of the red giant are in progress, to better understand the wealth of observational data available for the fascinating RS Oph recurrent nova.

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