

Recurrent Novae: Progenitors of SN Ia?

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Abstract. We present 3D hydrodynamical simulations of the separated binary RS Ophiuchi (RS Oph), a recurrent nova and potential progenitor of a SN Ia. RS Oph is composed of a red giant (RG) and a white dwarf (WD) whose mass is close to the Chandrasekhar limit. In an isothermal scenario, the WD accretes about 10% of a 20 km/s RG wind by a non-Keplerian accretion disk with strong spiral shocks, and about 2% of a 60 km/s RG wind by what we term a 'turbulent accretion ball'. A significantly larger impact have the thermodynamics. In an adiabatic scenario only about 0.7% of the 20 km/s RG wind is accreted. The rate of change of the system separation due to mass and angular momentum loss out of the system is negative in all three cases studied, but is ten times smaller for a fast RG wind (60 km/s) than for a slow RG wind (20 km/s). The results demonstrate that existing nova models and observed recurrence times fit well together with 3D wind accretion and that RS Oph is one of the most promising systems to become an SN Ia.

1. Introduction

Type Ia supernovae (SNe Ia) are cornerstones of modern cosmology as a measure for cosmological distances, and they are crucial building blocks of the universe, as production sites of a large part of iron group elements. In an SN Ia a white dwarf (WD) explodes after his mass has surpassed the Chandrasekhar stability limit. The existence of SN Ia thus is closely linked to the question of mass gain of the WD by accretion. The layer of accreted matter occasionally undergoes a thermonuclear runaway (nova) and much of the previously accreted matter is blown into space again. Based on 1D models, Yaron et al. (2005) find that a net mass gain of an already massive WD ($M \approx 1.4M_{\odot}$) occurs only for accretion rates above roughly $10^{-8}M_{\odot}\text{yr}^{-1}$. Moreover, to achieve a net gain of $0.05 M_{\odot}$ the WD must undergo many nova cycles, requiring a total time on the order of 1 to 10 million years.

Particularly interesting binary star systems in this context are recurrent novae (Anupama 2002). From the short decay time of their nova light curves

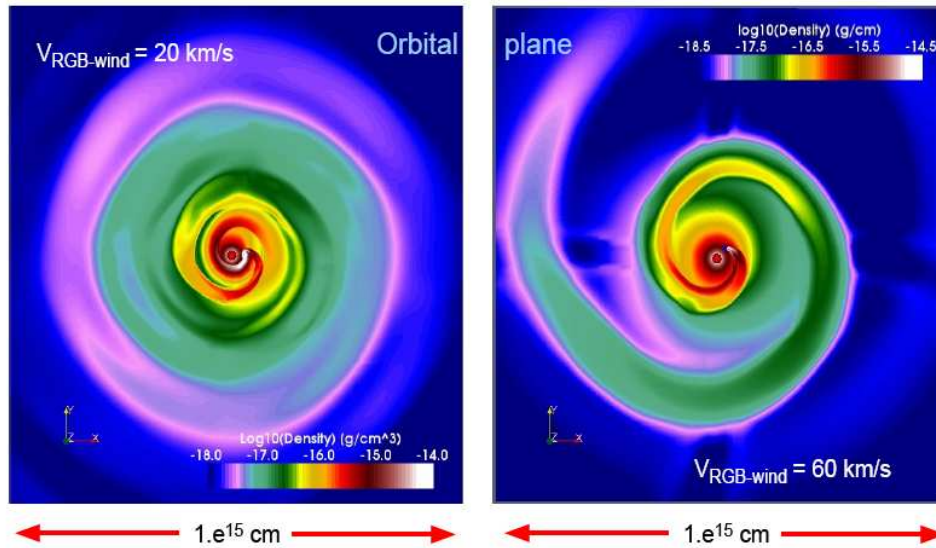


Figure 1. Density in orbital plane for slow (left) and fast (right) simulation.

the existence of an already massive WD close to $1.4M_{\odot}$ can be inferred. In the subclass of symbiotic-like recurrent novae, which we are interested in here, the secondary is a red giant (RG) star which undergoes a substantial mass loss in the form of a stellar wind. The RG typically does not fill its Roche lobe and mass transfer onto the WD occurs through wind accretion. The accretion efficiency then is on the order of 10% of the RG mass loss. Nevertheless, with a physically plausible RG mass loss rate of $10^{-7}M_{\odot}\text{yr}^{-1}$ the necessary WD accretion rates can be reached. Sustaining these conditions over several million years is not in a priori contradiction with typical RG life times. Symbiotic-like recurrent nova thus are plausible candidates for SN Ia progenitors, but a number of questions remain open.

The best observed system of this kind is RS Ophiuchi (RS Oph), which we investigated already in Walder et al. (2008) where we presented a 3D hydrodynamical simulation of the recurrent nova RS Oph during the accretion phase and nova outburst. Two issues we take up here again, in the light of new simulation data: accretion rates in a recurrent nova binary star system and the competition between mass loss and angular momentum loss out of the system. The latter is crucial as it affects the separation of the system and thus the accretion rate.

2. Model Problem and Numerical Method

The symbiotic-like binary star system RS Oph consists of a red giant and a white dwarf. The orbital period is 455 days (Fekel et al. 2000; Dobrzycka & Kenyon 1994). The system undergoes a nova outburst about every 22 years (Anupama 2002). For the most recent outbursts in 1985 and 2006, exquisite panchromatic observational data are available (Shore et al. 1996; Bode et al. 2006; Sokoloski et al. 2006; Das et al. 2006; O'Brien et al. 2006; Evans et al. 2006; Wouters

et al. 2007; Hachisu et al. 2007; Bode et al. 2007). We adopt masses of $2.3 M_{\odot}$ and $1.4 M_{\odot}$ for the RG and WD, respectively and a corresponding separation between the components of $a = 2.68 \cdot 10^{13}$ cm. We assume phase locking of the RG, a RG terminal wind velocity of either $v_{\text{RG}} = 20$ km/s (simulation slow) or $v_{\text{RG}} = 60$ km/s (simulation fast) in the rest frame of the RG, a mass loss rate of $10^{-7} M_{\odot}\text{yr}^{-1}$, and a wind temperature of 8000 K. The radius of the RG is smaller than its Roche lobe, accretion by the WD occurs from the RG wind.

We solve the Euler equations in 3D with a nearly isothermal polytropic equation of state with $\gamma = 1.1$, resulting in a thermal structure that comes close to that obtained from photoionization models of related symbiotic binary systems (Nussbaumer & Vogel 1987; Nussbaumer & Walder 1993). For comparison, we also did one adiabatic simulation with $\gamma = 5/3$ and $v_{\text{RG}} = 20$ km/s.

All simulations were performed with the hydrodynamical codes from the A-MAZE package (Walder & Folini 2000). The accreting system was relaxed to a quasi-stationary state. Mass and angular momentum losses out of the system were then computed through spherical shells around the center of mass. For further details on the simulation set up we refer to Walder et al. (2008).

3. Large scale patterns, accretion, system evolution

During the roughly 22 years of quiescence between successive nova outbursts, the circumstellar environment gets filled with RG material, which ultimately reaches out to several 10^{15} cm. The matter distribution on these large scales differs markedly between the slow and fast simulation, as shown in Fig. 1. In the slow case, the situation is fairly smooth and spherically symmetric. The spiral pattern in the equatorial plane is rather faint. A density contrast of a factor 2-3 between polar (less dense) and equatorial directions exists. This is sufficient to transform a symmetric nova outburst of the WD into an asymmetric nova remnant with an aspect ratio of about 2:1 (Walder et al. 2008). The observed nova remnant in RS Oph is asymmetric as well (O'Brien et al. 2006), a quantitative comparison remains to be done. For somewhat simpler underlying models, observable quantities have already been modeled and successfully compared with observations (Vaytet et al. 2007; Orlando et al. 2009). The fast simulation shows a much more pronounced, farther reaching spiral structure in the equatorial plane (Archimedean spiral). Density contrasts across spiral arms exceed one order of magnitude even at distances ten times the system separation. Densities in the polar direction are much more smooth.

The fast and slow simulation also show substantial differences in the accretion geometry around the WD, as shown in Fig. 2. In the case of the slow RG wind, accretion permanently takes place through a non-Keplerian disk in which angular momentum is transported via spiral shocks. In the case of the fast RG wind, the vicinity of the WD can rather be characterized as a supersonically turbulent accretion ball. Matter flows in from various directions and is redirected, slowed down, and thermalized by a complicated and rapidly changing network of shocks, while angular momentum is transported outwards. For a more thorough discussion of supersonic turbulence in a non-periodic setting see Folini & Walder (2006). The overall appearance of the vicinity of the WD is much more fluctuating than in the slow case. Disk-like accretion states also occur, but only

as transient features. In the slow wind case, densities around the WD are up to two orders of magnitude larger in the orbital plane than perpendicular to the orbital plane (Walder et al. 2008). In the fast wind case no such pronounced density contrast exists. The accretion rates change from around 10% \dot{M}_{RG} in the slow case to roughly 2% in the fast case. By contrast, the accretion rate is a mere 0.7% in the adiabatic simulation we performed.

In all the cases considered here, the cumulative effect of the system's mass and angular momentum losses points to a shrinking of the binary orbit. The loss of angular momentum more than outweighs the mass loss of the system and the two components spiral inwards. This picture is dominated by the quiescent phase of RS Oph, as only much less matter (around 10%) is involved in the occasional nova outburst. Absolute numbers turn out, however, to depend strongly on the RG wind velocity. Expressing the cumulated losses in terms of da/a with a the system separation, we find $da/a \approx 8 \cdot 10^{-8} \text{ yr}^{-1}$ in the slow case but about ten times less in the fast case, $da/a \approx 8 \cdot 10^{-9} \text{ yr}^{-1}$. Of much less relevance here are the thermodynamics. For $v_{\text{RG}} = 20 \text{ km/s}$ and $\gamma = 5/3$ we find $da/a \approx 6 \cdot 10^{-8}$.

4. Discussion and Conclusions

Our results further support the idea that the recurrent nova RS Oph is a good candidate for a progenitor of an SN Ia. In particular, the mass transfer rate required by nova models to reach a net mass gain over several nova cycles can be reached for reasonable system parameters. Also, the orbit of RS Oph is found to shrink under current conditions. Chances to maintain or even enhance the current mass transfer rate in the future thus are intact.

However, the three critical time-scales which determine the ultimate fate of the system are all of the same order. RG evolution models predict a high mass loss for a RG for some million years only. This time scale is similar to what is needed to shrink the orbit significantly and to the time necessary for the WD to accrete enough mass to become unstable.

To further investigate the possibility of RS Oph finally becoming a SN Ia simulation results should cover the long term evolution of the system and its components, over several nova cycles up to several million years. In addition, multi-dimensional nova models with better predictions of the mass gain condition of the WD would be most welcome. On the observational side, better estimates on the ejected mass in a nova outburst would be highly desirable to test the consistency with existing nova models and related accretion physics.

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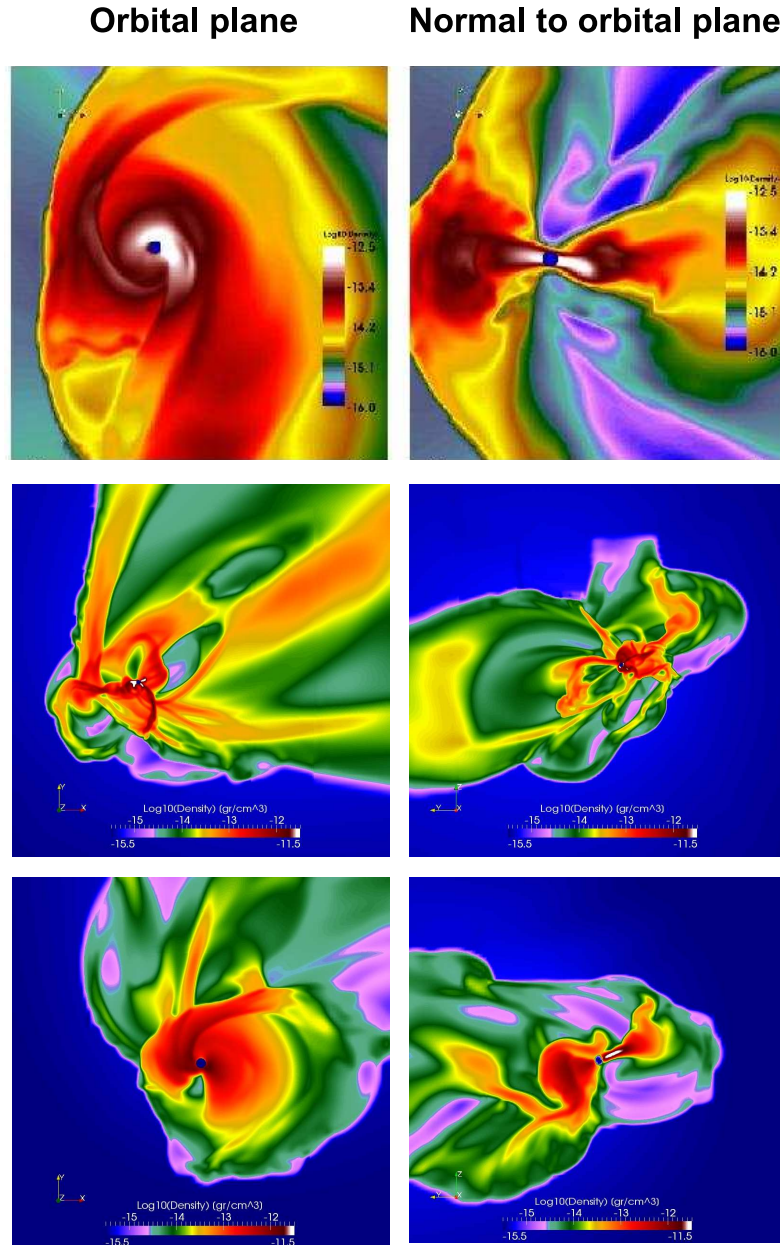


Figure 2. Accretion around the WD in the orbital plane (left column) and perpendicular to the orbital plane (right column) for $v_{RG} = 20$ (top row) and $v_{RG} = 60$ (middle and bottom row). Shown is density, logarithmic scale. In the $v_{RG} = 20$ case, occurs permanently through a non-Keplerian disk with spiral shocks. In the $v_{RG} = 60$ case, accretion occurs predominantly through a 'turbulent accretion ball' (middle row) but occasionally also through a non-Keplerian disk (bottom row), similar to the $v_{RG} = 20$ case. The spatial scale of each of the above panels is roughly 10^{13} cm.

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