PROCEEDINGS OF SCIENCE

3D Hydrodynamical Simulations of Nova Ejecta: Pollution of the Companion Star

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Classical novae are cataclysmic binary star systems in which matter from an unevolved star is slowly accreted by a white dwarf companion. When enough mass has been accreted the pressure at the base of its envelope becomes high enough for the ignition of hydrogen, and a thermonuclear runaway occurs. Apart from releasing a large amount of energy in various parts of the electromagnetic spectrum, the nova explosion also results in the ejection of matter, forming an expanding shell around the system. In this study we aim to investigate the evolution of this nova shell to ascertain whether or not the secondary star can be significantly polluted by the ejecta material. To model the expanding shell we use a smooth particle hydrodynamics (SPH) code. The simulation is fully 3D and includes the nova ejecta, the main sequence companion, and the white dwarf (as a gravitational potential). The initial conditions for the nova ejecta are taken from the late stages of a detailed 1D hydrodynamical-nucleosynthetic simulation of the nova outburst on the white dwarf surface. Our very preliminary results show that some matter is accreted by the companion star, as expected, however it remains to be seen if the amount accreted is significant. We also find that the impact of the shell material on the main sequence star envelope enhances mass transfer in the system, so that some ejecta is probably also re-accreted by the white dwarf itself. This will affect the next nova explosion, as the white dwarf surface composition will be altered, especially at low metallicity. We also discuss necessary improvements for our future simulations.

11th Symposium on Nuclei in the Cosmos, NIC XI
July 19-23, 2010
Heidelberg, Germany

*Speaker.

1. Introduction

Classical novae (CN) are close binary systems composed of a white dwarf (WD) slowly accreting matter ($\dot{M} \sim 10^{-10} \rightarrow 10^{-9}$ $M_\odot$ yr^{-1}) from a main sequence (MS) companion. As the matter is accreted the pressure at the bottom of the WD's forming envelope increases. A critical point is reached when pressure is high enough to ignite hydrogen ($P_{crit} = 10^{19} - 10^{20}$ dyn cm^{-2} [1]). Due to the fact that the matter is partially degenerate a thermonuclear runaway (TNR) ensues that leads to the release of so much energy over such a short amount of time that the envelope becomes unbound [2], forming an expanding shell of gas that soon impacts on the companion star. The ejecta from some of these events have now been spatially resolved by high resolution telescopes, for example Nova Cygni 1992 by HST (see eg. Fig. 1 of [3]).

One dimensional hydrodynamic studies of nova explosions (eg. [2, 4, 5]) show that the material ejected from a nova has been subject to high temperature, non-equilibrium hydrogen burning. It thus carries the nucleosynthetic signature of this burning – high abundances of ^{13}C, ^{15}N, ^{17}O – and novae are expected to be important Galactic producers of these nuclei. Moreover, it has been inferred by observations that significant mixing occurs between the WD carbon-oxygen core and its accreted envelope, such that the metallicity can rise as high as $Z \sim 0.2 \rightarrow 0.8$ at the surface (see eg. the review by [6], and theoretical studies by eg. [7], [8]).

In a nova explosion almost all of the accreted envelope is ejected ($\sim 10^{-5} \rightarrow 10^{-3}$ $M_\odot$). The cycle then starts again, starting with the long accretion phase. It is usually assumed that the material accreted by the WD during this phase will be pristine MS star material. However if during the previous nova explosion part of the ejected material is accreted by the companion and then re-accreted by the WD, then the metallicity in the WD envelope might be higher than expected. This becomes particularly important in low metallicity novae, since the metallicity of the accreted material determines the nucleosynthesis (and thus energy release) of the nova explosion [9]. This scenario could also be relevant in terms of condensates that form in the interaction between the ejecta and the MS material – this may be the source of the dilution that is required to understand the presolar grains of putative nova origin [10]. The current study aims to investigate the physical evolution of the ejecta material just after it is expelled from the WD, in order to ascertain if there is any pollution of the companion, and/or re-accretion by the WD.

2. Method

To follow the gravitational and hydrodynamical evolution of the ejecta and its effect on the MS star we use a modified version of the SPH code *STARCRASH* [11, 12, 13]. SPH is a Lagrangian method, so it is well suited to the problem which involves material moving with complex geometries and expanding without boundaries. As a first approximation we have assumed an ideal gas with a polytropic equation of state ($\Gamma = 5/3$).

One of the limitations of SPH is that interactions between SPH particles of significantly different masses ($>$ factor of a few) give rise to spurious forces. For this reason it was necessary to match the particle masses in the MS companion star with those of the nova ejecta. However to do this and maintain a reasonable level of resolution in the ejecta would require $\sim 10^8$ particles in the MS star alone, and thus would be impractical with our current computing resources. To circumvent this problem we have modelled only 0.028 $M_\odot$ of the outer envelope of the 1.0 $M_\odot$ MS star, and represented the rest of the star with a central point mass. This envelope mass corresponds to the outer ~ 0.1 $R_\odot$ of the star, which has a polytropic density profile with $\gamma = 5/3$. The envelope is supported by an inner shell of fixed boundary particles that has a depth of ~ 0.05 $R_\odot$. At the base of the envelope the average (adaptive) SPH smoothing length is $\langle h \rangle \sim 0.02$ $R_\odot$, so that particles near the inner boundary always have sufficient boundary particle neighbours within the interaction radius of $2h$. In Fig. 1 we show the density profile of the MS star envelope after relaxation. It is this density profile that the nova ejecta will interact with during the impact. We note however that in the current simulation we have neglected the WD potential during relaxation (see discussion in Section 3).

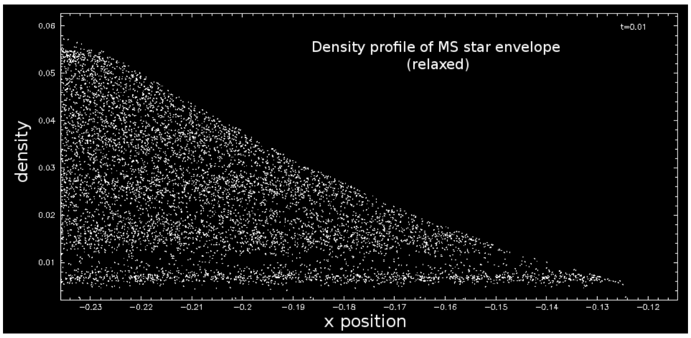

Figure 1: Relaxed density profile of SPH particles in the companion star envelope. Position units are in $R_\odot$, with the centre of mass of the binary system at the origin.

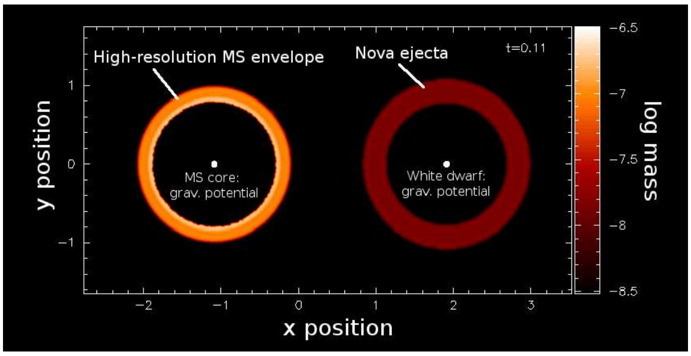

Figure 2: Orbital plane cross section of the initial setup. The MS star (point mass core + high resolution envelope) is on the left, and the WD surrounded by the low density ejecta is on the right. Position units are in $R_\odot$, with the centre of mass at the origin.

We model the WD as a gravitational potential of mass 0.6 $M_\odot$, (a typical WD mass) around which a spherical nova ejecta shell is placed. Taking a 1D hydrodynamical model as a guide [14], the ejecta shell is modelled as initially having a constant density and a thickness of 0.25 $R_\odot$. The initial outer radius is taken as 1.0 $R_\odot$. The shell is given a linear velocity profile, such that the inner edge of the shell has $v_r = 500$ km s^{-1} and the outer edge has $v_r = 1000$ km s^{-1}, again using the 1D model as a guide. The binary separation is 3 $R_\odot$, such that the MS star does not quite suffer Roche Lobe overflow (RLOF). Thus the outer edge of the ejecta will take ~ 12 minutes to reach the surface of the MS star and the corresponding binary period is ~ 9.5 hrs. This period is at the longer end of the classical novae period distribution (eg. [15]). We plan to explore systems with different binary parameters in the future. The total mass of the ejecta is 2.0×10^{-3} $M_{\odot}$ (at the upper end of mass ejection from novae). In Fig. 2 we show the full initial setup, which has 919,311 SPH particles in total.

3. Preliminary Results and Discussion

The simulation was run on a parallel supercomputer using 32 processors. Total energy was conserved to better than 1% during the simulation. In Fig. 3 we show two density plots at various stages during the impact. In the left panel it can be seen that there is a phase where the ejecta compresses the MS star's envelope. At this stage there is also some reflection off the MS star, a sort of 'blow-back' towards the WD. This material may be re-accreted by the WD. The right panel shows another interesting phase, at a later time – the envelope is expanding in response to the impact. This is significant because the MS star is just at the point of RLOF and any extension of the envelope caused by the ejecta impact will thus lead to enhanced mass transfer to the WD, since the expanding envelope material will be dominated by the gravitational potential of the WD.

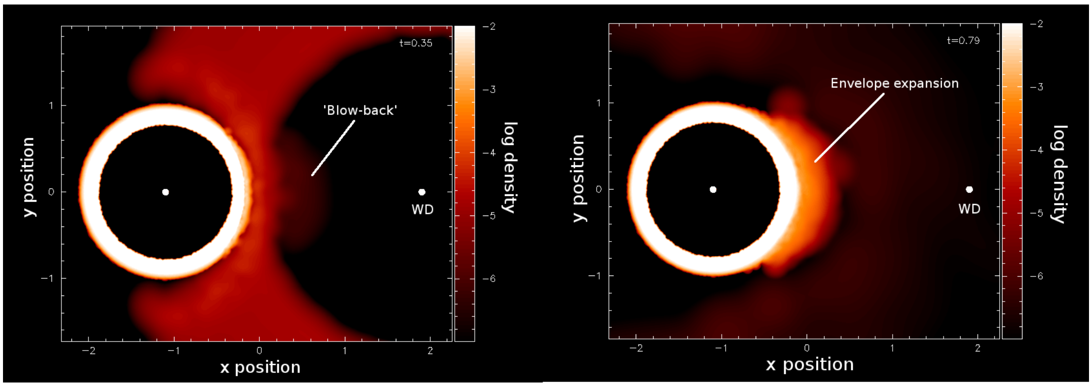

Figure 3: Cross section log density plots at two different stages of the simulation. Density units are $g\ cm^{-3}$ and x,y position units are $R_{\odot}$. *Left:* Early stage of ejecta impact – 'blow-back' and envelope compression. Time (t) is in code units, corresponding to a real time of ~ 32 min. *Right:* Late stage of impact – envelope expansion and possible accretion by white dwarf. Time corresponds to ~ 72 min.

Although our results are very preliminary we speculate on some possible outcomes. Enhanced mass transfer and re-accretion of the nova ejecta by the WD would affect the composition of the WD envelope, thus altering the characteristics of the next nova explosion. As mentioned earlier, this can have a strong effect on low-metallicity nova explosions. We plan to perform further, improved simulations, in order to quantify the WD re-accretion and any accretion of nova ejecta by the MS star. Future simulations will include the orbital motion of the stars since, although the explosion occurs on a much shorter timescale than the orbital period, the centrifugal force needs to be included to realistically track the gas. Also, although the WD gravity was included in the simulation during the nova ejection phases, the MS envelope was not relaxed in this potential. Both of these effects could alter the tentative conclusions arrived at through our preliminary simulations. Furthermore the binary configuration will need to be altered to determine how the binary parameters (masses of the stars, orbital separation, etc.) affect the results. Tidal deformation can be important if the stars are sufficiently close together. Further improvements will be to include more detailed physics, such as a more realistic equation of state and to track chemical species.

Acknowledgments

SWC acknowledges the support of the Consejo Superior de Investigaciones Científicas (CSIC) via a JAE-DOC postdoctoral fellowship. Calculations were made on the Australian National Facility supercomputer, under Project *g*61. The rendered SPH plots were made using the freely available *splash* code written by Daniel Price [16].

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