Not-So-Super Novae; The Classical Model

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The vast majority of stars in the universe will not end their lives in a spectacular supernova. Instead, as they run out of hydrogen fuel, they will throw off their outer layers while their core contracts into a degenerate sphere of nuclear ash: a white dwarf. Most white dwarfs will proceed to spend the following eons doing little but slowly cooling. Some, however, will not be so quiet. If a white dwarf finds itself in a binary system with a nearby companion, it may eventually produce one of the largest thermonuclear explosions in the universe: a nova. There is one particular trait that makes these atomic blasts different from most other natural or artificial explosions, they are often cyclical.

The term "nova" itself derives from latin, meaning literally "a new star." Ironically, the white dwarf progenitor of the explosion is neither new nor a star. Novae originate from binary star systems wherein a white dwarf is close enough to a non-degenerate companion to allow mass-transfer and accretion of hydrogen onto the white dwarf's surface. As the quantity of material in this hydrogen layer grows, its pressure and temperature increase to the point where CNO fusion occurs. This triggers a thermonuclear runaway (TNR) reaction that rapidly consumes the accreted hydrogen layer, generating a massive burst of radiation and throwing out a cloud of ejecta (Wolf et al., 2013). In cases where the mass loss is less than the mass accreted, the white dwarf has a net positive mass change. Over successive generations of novae, this growth may push the white dwarf close to the Chandrasekar limit ~ 1.4 $M_\odot$. If that occurs, the electron-degeneracy process will no longer be sufficient to support the remnant's mass and it will destabilize in a massive explosion, potentially consuming the entire white dwarf. This is thought to be a possible mechanism behind Type-Ia supernovae (Wolfe et al., 2013). This sequence of events obviously has many caveats and exceptions, however decades of theory and simulation research have largely agreed that the nature of white dwarf novae can be almost entirely explained by the interplay of three parameters: white dwarf temperature, white dwarf mass, and the rate of mass transfer (Yaron et al., 2005).

The most well subsection of this parameter space corresponds to what is called the classical nova model (Yaron et al., 2005). A representation of this cycle is shown in Fig. 1, a combination of two plots from a 1986 paper by Dina Prialnik. This model considered a 1.25 $M_\odot$

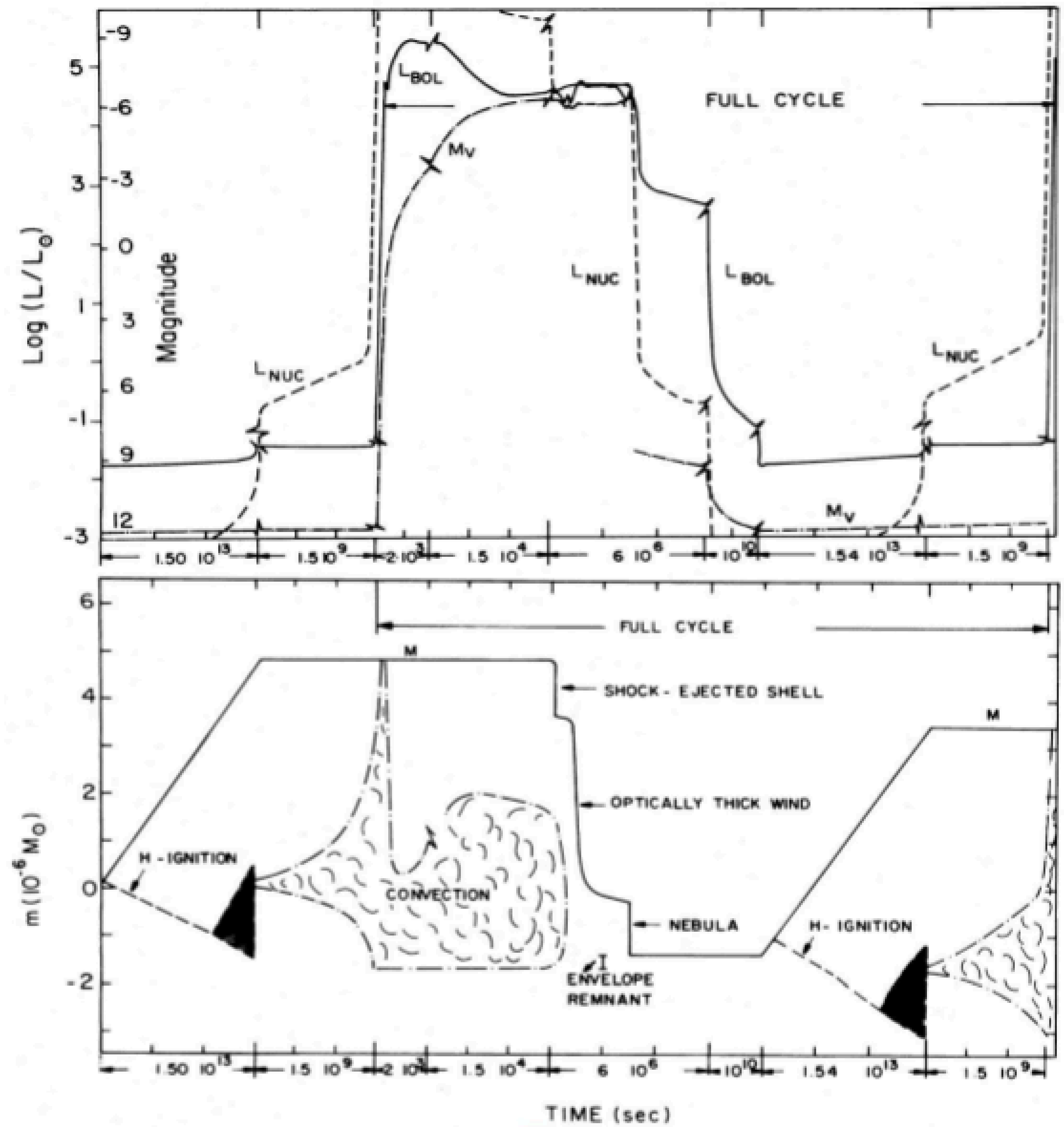

Fig. 1. (Top) Luminosity vs time plot for a classical nova cycle. The x-axis is segmented into time blocks as indicated. L_{bol} is the bolometric luminosity, L_{nuc} is nuclear luminosity, and the dashed-dotted line is the visual magnitude. (Bottom) Mass structure vs time plot on the same time axis. The y-axis is mass above/below the original size of the white dwarf. This can be thought of an analogue to radius, so m = 0 marks the original radius of the white dwarf (Prialnik, 1986).

white dwarf with a surface temperature of 5 million K and a mass accretion rate of 10^{-11} $M_{\odot} yr^{-1}$. Prialnik divided the classic nova cycle into six distinct phases: outburst, rapid expansion, mass-loss, decline, accretion, and convection (Prialnik, 1986).

This is a simplification of the model and significant detail was omitted from this summary. During the TNR outburst phase, convection-driven energy transport drives the formation of a large shock wave, which begins to rapidly push material outward. The runaway itself only lasts for a matter of minutes. The shock drives the expansion of the material to a radius of ~ 100 $R_\odot$ while it also cools to ~ 9000 K. Interestingly, this set of conditions would appear very similar to an A-type supergiant star. Over a time period of roughly a month, the majority of the material from the accreted shell expands outward, while the small fraction of still-bound material quickly contracts back onto the white dwarf. In another curious parallel, this process is effectively a miniature version of the original formation of a planetary nebula around the white dwarf. It is predicted that the mass transfer process would restart almost immediately, however it will not become a dominant process for several hundred years. In the meantime, the primary activity on the white dwarf is simply slow cooling and contraction. Around 8000 years of steady accretion of material over the cooling white dwarf follows. There is some diffusion of material between the hydrogen layer and the white dwarf and the re-ignition of hydrogen fusion actually occurs during this period. However it remains weak until near the end of the accretion phase. Eventually the energy output from fusion exceeds the bolometric luminosity of the white dwarf, causing the layer of burning hydrogen to destabilize and form a convective region. Over the following several decades, this convection zone expands outward into the hydrogen layer as well as downward into the white dwarf. When the convection zone finally reaches the surface of the accretion layer, a rapid increase in luminosity marks the start of TNR and the completion of a nova cycle (Prialnik, 1986).

An important development in nova models after Prialnik and others' initial work was the development of multicycle models using improved simulation code and more powerful computers. (Yaron et al, 2005). In a follow up to an earlier paper, Yaron, Prialnik, and collaborators worked to expand simulations outward in the 3D parameter space defined by the previously mentioned quantities: accretion rate, white dwarf mass, and white dwarf temperature. They found that a surprisingly wide range of conditions could lead to classical novae behavior. More extreme combinations of parameters were noted as resembling observations of strange novae that had not been previously reproduced in other simulations. The parameter space itself resembles a tube or cylinder, as shown in Fig. 2. The space becomes a closed volume when temperature constraints for electron degenerate matter are added (Yaron et al, 2005).

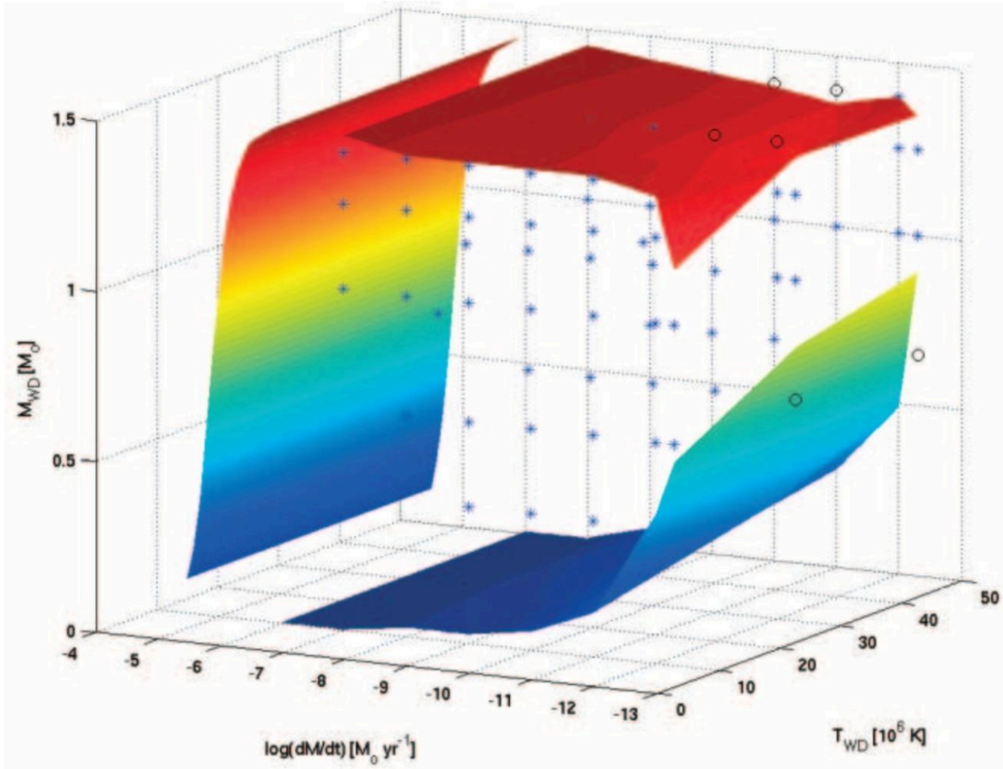

Fig. 2. A 3D plot highlighting the parameter space compatible with the classical nova model. The axes are white dwarf temperature in 10^6 K, white dwarf mass in M⊙, and the log of the mass transfer rate in $M_\odot yr^{-1}$ (Yaron et al, 2005).

In conclusion, the classical nova model has been the dominant model for the majority of observed nova for several decades. While much of the underlying theory remains the same, more recent simulations have expanded the parameter space associated with this model. By examining different combinations of initial conditions outside this classical parameter space, these simulations have also begun to shed light on previously unreproduced observations of exotic nova-like events. However, the long-standing classical model continues to be a robust and useful approach to explaining the astrophysics behind novae. One could argue that perhaps the classical model has actually been too successful, as now it seems research into novae is much less active than it once was. So while researchers turn their attention to the more shiny and exciting kilonovae, supernovae, and hypernovae, it does not hurt to look back and remember the original "new stars."

References

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