The 2D evolution of Nova from the onset of convection to outburst

Kavli Institute - March 15 2007

Ami Glasner , Eli Livne
The Hebrew University, Jerusalem

&

Jim Truran
The University of Chicago
Former results
Semianalytical models & Dimensional considerations

- **Shara** *(ApJ 243, 926; 1982)*
  
  “Volcanic” localized eruptions → early perturbations?

- **Fryxell & Woosley** *(ApJ 261, 332; 1982)*
  
  Dimensional analysis of multidimensional effects for TNRs that occur on thin stellar shells.

  Claim that for the Nova case there is initiation at a point and a flame that spreads by small scale turbulence with velocity:

  \[ v = \left( \frac{h_p v_c}{\tau_b} \right)^{1/2} \]
Who?  How?

Shankar, Arnett & Fryxell
PPM

Kercek, Hillebrandt & Truran
PPM
2D (A&A 337, 379; 1998)
3D (A&A 345, 831; 1999)

Glasner, Livne & Truran
ALE

Flash PPM
The main Issue:

The reliability of the mixing results?
Abundances - Observations
ON THE FREQUENCY OF OCCURRENCE OF OXYGEN-NEON-MAGNESIUM WHITE DWARFS IN CLASSICAL NOVA SYSTEMS

JAMES W. TRURAN AND MARIO LIVIO

Department of Astronomy, University of Illinois

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TABLE 2

HEAVY-ELEMENT ABUNDANCES IN NOVAE

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ABUNDANCE ANALYSIS OF THE EXTREMELY FAST ONeMg NOVAE V838 HERCULIS AND V4160 SAGITTARII

GREG J. SCHWARZ
Department of Geology and Astronomy, West Chester University, West Chester, PA; gschwarz@as.arizona.edu

STEVEN N. SHORE
Dipartimento di Fisica "Enrico Fermi,” Università di Pisa, I-56127 Pisa, Italy; INFN-Sezione di Pisa; shore@df.unipi.it

SUMNER STARRFIELD
School of Earth and Space Exploration, Arizona State University, Tempe, AZ; sumner.starrfield@asu.edu

AND

KAREN M. VANLANDINGHAM
Department of Geology and Astronomy, West Chester University, West Chester, PA; kvanlandingham@wcupa.edu

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TABLE 6
MASS FRACTION COMPARISON OF FIVE RECENTLY MODELED ONeMg NOVAE

<table>
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<th>Element</th>
<th>QU Vul</th>
<th>V1974 Cyg</th>
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<th>V4160 Sgr</th>
<th>V838 Her</th>
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NOTE.—Where the H + He + Z = 1.

a Solar values were assumed for elements that did not have reported abundances.
Mixing Mechanisms
Mixing mechanisms effect on burning and nucleosynthesis

Mechanisms:

- Diffusion
  (Prialnik and Kovetz, Iben Fujimoto and MacDonald)
- Shear induced mixing
  (Kippenhan&Thomas, MacDonald, The flash team-Chicago)
- Undershoot of convective flows
  (Woosely, Glasner Livne&Truran, Kercek Hilllebrandt & Truran)
Diffusion

- Takes place on the longest time scales (accretion).
- Mixing once the envelope becomes unstable to convection.
- The amount of mixing depends on the accretion rate.
- $Z$ enrichment in simulations $\sim Z$ observed.
Fig. 2.—Heavy-element (Z) profiles for D14 at different times. Mass scale as in Fig. 1.

All the mixing takes place prior to the runaway!
shear

- Shear Instability in the stratified boundary between the core and the accreted envelope associated with the accretion disk.
- Resonant interaction of the shear flow with gravity (ocean) waves in the core.
- Very early creation of boundary mixed layer
- Mixing once the envelope becomes unstable to convection.
Convective undershoot Mixing
The New Models
Why do we need more work?

- Initial model at earlier stages ➔ close to the onset of convection
- The evolution of early perturbations
- Resolution –
  a) KH limit on wave length: \( k \gtrsim \frac{g}{U_{max}^2 (1 - \rho_1/\rho_2)} \)
    \[ \text{Umax} \sim 100 \text{ km/sec} ; \text{g} \sim 5 \times 10^8 \text{ cm/sec}^2 \]
    \[ k \sim 10^{(-6)} \] ➔ wavelength \( \sim 10^6 \text{ cm} \)
  b) numerical convergence
- Improving the numerical schemes
- Steep gradients at the base of the envelope
- Base Temperature of $10 \times 10^7$ Deg
- In 1D unstable to convection at $T_{base} \sim 3e7$ Deg
The Simulated part of the star

cylindrical symmetry axis
The initial model consists of a $1.14 \ M_\odot$ CO white dwarf in hydrostatic and thermal equilibrium, cooled to the stage at which the luminosity of the WD is about $1.6 \times 10^{-2} \ L_\odot$. Using a 1D hydro-evolution code (Glasner & Truran 2007), matter with solar abundances (Anders & Grevesse 1989) is accreted onto the surface of the CO core continuously at a rate of $1.0 \times 10^{-9} \ M_\odot \ yr^{-1}$. The elements included in our reaction net are: $^1H$, $^3He$, $^4He$, $^7Be$, $^8B$, $^{12}C$, $^{13}C$, $^{13}N$, $^{14}N$, $^{15}N$, $^{14}O$, $^{15}O$, $^{18}O$, $^{17}O$, $^{17}F$. Diffusion and mixing of the chemical elements between the accreted envelope and the core are not included in the 1D code. The total amount of accreted matter at the time of runaway is $3.5 \times 10^{-5} \ M_\odot$.

**grid:** $1.4 \ km \times 1.4 \ km$

Typical values are:

$$V_{early\text{-}convection} \approx 50 \ Km/sec$$

where $V_{early\text{-}convection}$ is the typical local early convective velocity.

$$V_{late\text{-}convection} \approx 1000 \ Km/sec$$

where $V_{late\text{-}convection}$ is the typical local late convective velocity.

$$V_{sound} \approx 2000 \ Km/sec$$

where $V_{sound}$ is the typical speed of sound prior to the peak of the runaway.
Kelvin – Helmholtz instability
lines of equal C(12) abundance

Glasner Livne & Truran 1997 (fig.2)
Improved grid resolution

New

Old
Demonstration of the sensitivity to the outer boundary conditions

The ability to work “Lagrangian” at the outer zones and “Eulerian” near the burning regions
The reference Models

- T7 - Base temperature of $7 \times 10^7$ Deg K
- T9 - Base temperature of $9 \times 10^7$ Deg K
- T5 and lower $\Rightarrow$ the difficulties.
Fig. 3.— The logarithm of the total energy production rate [erg/sec] (Q) as function of time for models T5, T7 and T9: top-left - nominal times, top-right - the line for model T9 is shifted forward by 264 seconds, bottom - the line for model T9 is shifted forward by 1464 seconds and the line for model T7 by 1200 seconds.
Control Parameter Total Energy Production Rate $Q$ [erg/sec]

Check points:
Log$(Q) = 42, 44, 45$

At $Q = 10^{45}$ erg/sec
$Q^*(a\ few\ sec) = \text{Binding energy of the envelope}$
The overall picture
Fig. 1.— C12 abundance for model T7: top left - when $Q = 10^{42}$ erg/sec, top right - when $Q = 10^{43}$ erg/sec, bottom left - when $Q = 10^{44}$ erg/sec, bottom right - $Q = 10^{45}$ erg/sec, note that the colors limit change from one frame to the other.
Fig. 2.— Velocity field in model T7: top left - $Q = 10^{42}$ erg/sec, top right - $Q = 10^{43}$ erg/sec, bottom left - $Q = 10^{44}$ erg/sec, bottom right - $Q = 10^{45}$ erg/sec. The velocities are scaled, the highest velocities in the bottom right are about 1000 Km/sec.
The details…
Fig. 5.— Lateral average of $Q$ as function of the fractional mass for models T7 and T9: top-left - when $Q = 10^{42}$ erg/sec, top-right - when $Q = 10^{42}$ erg/sec, bottom - when $Q = 10^{45}$ erg/sec
Fig. 4.— Lateral average of the temperature as function of the fractional mass for models T7 and T9: top-left - when $Q = 10^{42}$ erg/sec, top-right - when $Q = 10^{43}$ erg/sec, bottom - when $Q = 10^{45}$ erg/sec
Fig. 6.— Lateral average of the CNO abundance as function of the fractional mass for models T7 and T9: top-left - when $Q = 10^{42}$ erg/sec, top-right - when $Q = 10^{42}$ erg/sec, bottom - when $Q = 10^{45}$ erg/sec
$T=38$
Numerical Tests

- Angular range of the grid (same resolution).
- ALE vs. “Effective Lagrangian”
Fig. 9. — Velocity Field of models $T7$ and $T7_{Wide}$ at $t=300$ sec (R and Z in Km)
Angular dimensions 0.06*PAI vs. 0.12*PAI

Fig. 8. — Model T7 vs. T7\text{Wide}: left - The logarithm of the total energy production rate $Q$ [erg/sec] as function of time [sec] right - The CNO abundance as function of mass when $Q = 10^{43}$ erg/sec.
The Fate of Early Perturbations

Local perturbation

H rich (solar)

C-O

(O-Ne-Mg)

1D Temperature history

$\frac{dT}{dt} = 5 \cdot t$

$\Delta t \approx 10^8$ sec

$R \approx 5 \cdot 10^8$

d $\approx 10^8$

$T_{mp} = 10^8$ K
In order to study the consequences of early perturbations the initial model T7 was used as a base line. The model was evolved for 20 seconds in the ALE explicit mode until the convective velocity structures in 2D were fully established. Fluctuations in the convective flow are expected to change the local temperature distribution. The perturbations that are expected to have the largest impact on the flow are those that occur at the base of the envelope and impose also some dredge-up of CO matter from the core. Therefore, at this stage we examine the differences between the evolution, from $t=20$ seconds and on, of the reference case (Model T7) and a model for which we impose a perturbation at the sensitive region defined above (Model $T7_{Perturb}$). The perturbed region includes a significant part of a convective cell and a few zones of the underlying CO core matter ($\Delta R = 7Km$ and $\Delta Z = 14 Km$). The abundances of the whole region are fully mixed and the temperature enhanced up to $9 \times 10^{7} \, ^\circ K$. The whole procedure was repeated for the wide grid (Model $T7_{Perturb-Wide}$) with its reference model (Model $T7_{Wide}$).
Wide T=20
Fig. 12. — Velocity field and C12 abundance for model $T_{\text{Perturb}}-\text{Wide}$: top - at time 20 Sec, bottom - at time 26 sec. Velocities are scaled so that the highest velocities are 500 Km/sec.
FIG. 11.— models T7, T7_Perturb, T7_Wide and T7_Perturb_Wide left - The logarithm of the total energy production rate [erg/sec] as function of time [sec] right - Lateral average of the CNO abundance as function of mass
Special features of the Undershoot Mechanism
Fig. 7.—model T7 when $Q = 10^{42}$, $10^{43}$ and $10^{45}$ left - Lateral average of $\log(q)$ vs. mass; right - Lateral average of $\log(q/q_{\text{limit}})$

$$q_{\text{max}} = 5.8 \times 10^{13} \times \left(\frac{Z_{\text{CNO}}}{0.01}\right)[\text{erg/gram/sec}]$$
Discussion

- Universality Mixing at the level of 30-50%
  - The origin
  - How far back can we go?

- Mixing
  - observations vs. mechanisms
    is there a discriminator?
    are they all contributing? Relative importance?
  - physical vs. numerical mixing
    what else can be done?

- Future models? 3D?
Fig. 15. — The logarithm of the total energy production rate [erg/sec] as function of time [sec] for all the models. The lines were shifted in time in order to show the universality of the models.
Fig. 13.— Logarithm of the specific burning rates of a mixture of hot solar abundant material and cold CO as function of the fraction of the cold CO for various temperatures.
Fig. 14.— The maximal enhancing factor that can be achieved by mixing as function of the temperature of the hot matter.
How far back can we go?

TABLE 1
Typical evolutionary timescales to the runaway from various initial temperatures at the base of the hydrogen rich envelope. Given for: 1D accreting solar, 1D accreting enriched mater (52.5% $H$, 12.5% $^{12}C$, 12.5% $^{16}O$) and the 2D models.

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<th>$\Delta t$ 1D enriched [sec]</th>
<th>$\Delta t$ 2D [sec]</th>
<th>no. of timesteps 2D</th>
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<td>$3 \times 10^7$</td>
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<td>$5.2 \times 10^6$</td>
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<td>NA</td>
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<tr>
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<td>$1.9 \times 10^5$</td>
<td>NA</td>
<td>NA</td>
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<td>$\approx 7 \times 10^6$</td>
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<td>$\approx 2 \times 10^6$</td>
</tr>
<tr>
<td>T9</td>
<td>$9 \times 10^7$</td>
<td>$3.2 \times 10^3$</td>
<td>$8.0 \times 10^2$</td>
<td>150</td>
<td>$\approx 6 \times 10^5$</td>
</tr>
</tbody>
</table>