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Lecture IV: Some Consequences of Accretion in Binary Systems

- ❑ Accretion Triggered Thermonuclear Runaways
 - ❑ hydrogen TNRs on the surfaces of white dwarfs : novae
 - ❑ H, He TNRs on the surfaces of neutron stars: X-ray bursts
 - ❑ accretion-induced growth of white dwarfs to SNe Ia

Summer School in Nuclear Physics
Laurence Berkeley National Laboratory

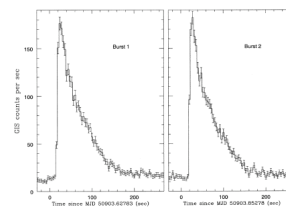
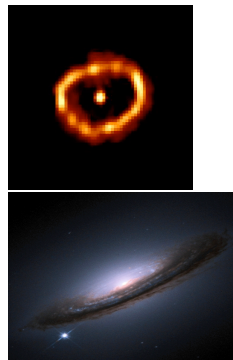
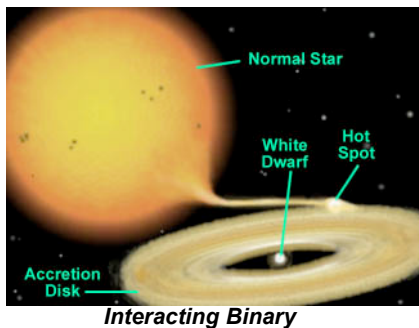
June 6-10, 2005

Focus of Flash Center Astrophysics

To simulate matter **accretion** onto the surfaces of compact stars, **nuclear ignition** of the accumulated (and possibly stellar) material, and the subsequent evolution of the star's interior, surface, and exterior.

- ❑ Type Ia supernovae (in white dwarf interiors)
- ❑ Novae (on white dwarf surfaces)
- ❑ X-ray bursts (on neutron star surfaces)

These events have in common the fact that they involve ignition of nuclear fuels under degenerate conditions, leading to thermonuclear runaways and astrophysical explosions.

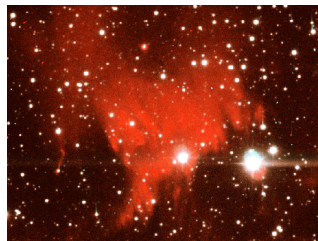
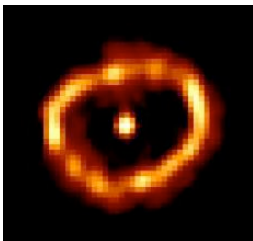
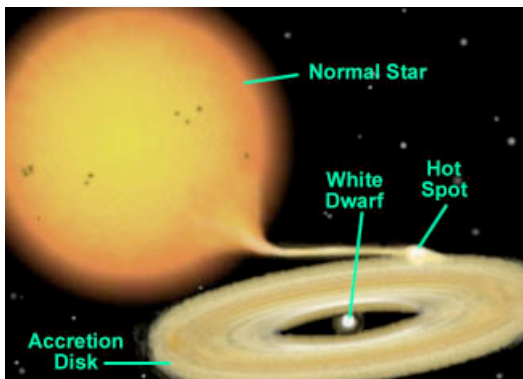


X-ray burst: GS 1826-24

Accretion onto White Dwarfs and Neutron Stars

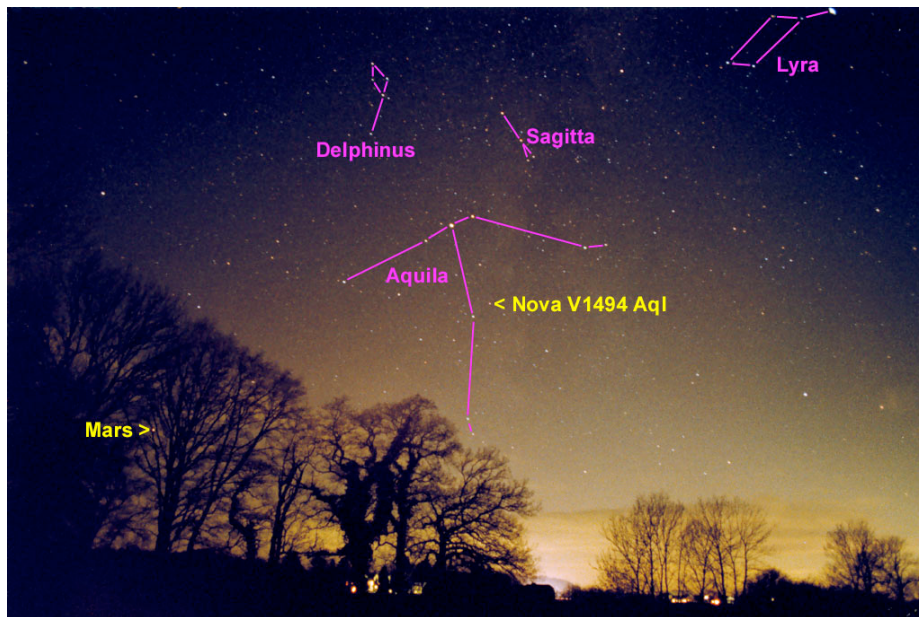
- ❑ The occurrence of white dwarfs and neutron stars in close (and interacting) binary systems can lead to a range of interesting phenomena.
 - ❑ Hydrogen accretion onto white dwarfs leads to hydrogen thermonuclear runaways: defining **novae**.
 - ❑ Hydrogen accretion onto neutron stars leads to H-He thermonuclear runaways: defining **X-ray bursts**.
 - ❑ The energetics of these two cases can differ significantly.
 - ❑ The nuclear energy release in the conversion of hydrogen to helium in Solar matter is $\approx 6 \times 10^{18} \text{ erg g}^{-1}$.
 - ❑ The gravitational binding energy per gram for a $M_{\odot}$ white dwarf is $\approx 3 \times 10^{17} \text{ erg g}^{-1}$, while that for a $1.4 M_{\odot}$ neutron star of radius 15 km is $\approx 10^{20} \text{ erg g}^{-1}$.
- ⇒ **nuclear energetics dominate novae but not X-ray bursts !**

The “Standard Model” for Classical Novae



- ❑ What are Classical Novae?
 - ❑ Thermonuclear explosions in hydrogen-rich envelopes on white dwarfs in close binary systems.
- ❑ How does evolution proceed?
 - ❑ Accretion of matter from a companion leads to growth of the envelope until a critical pressure is achieved at its base to trigger a thermonuclear runaway.
- ❑ Why is the outburst so violent?
 - ❑ A combination of degenerate conditions at the base of the envelope and the “dredge-up” of C, O, and Ne fuels from the white dwarf core yields rapid energy release on a dynamic time scale.

Nova V1494 Aql



Characteristics of Nova Systems

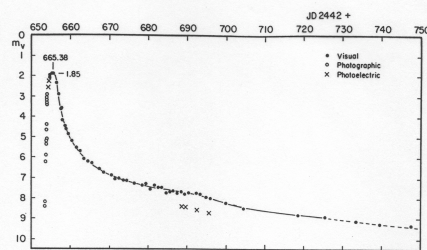


Figure 17.17 The light curve of V1500 Cyg, a fast nova. (Figure adapted from Young, Corwin, Bryan, and De Vaucouleurs, *Ap. J.*, 209, 882, 1976.)

Nova V1500 Cyg 1975

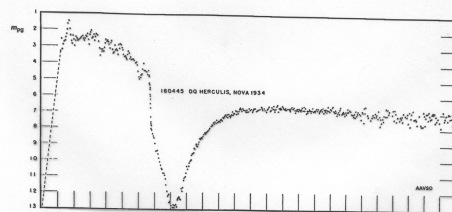


Figure 17.18 The light curve of DQ Her, a slow nova. The photographic magnitude, m_{pg} , is measured from the nova's image on photographic plates. (Courtesy of Janet A. Mattei, AAVSO Director.)

Nova DQ Her 1934

Nuclear Physics of Novae Anticipated

Three Europeans in India, looking at a great new star in the Milky Way. These were apparently all of the guests at a large dance who were at all interested in such matters. Amongst those who were at all competent to form views as to the origin of this cosmoclastic explosion, the most popular theory attributed it to a collision between two stars, or a star and a nebula. There seem, however, to be at least two possible alternatives to this hypothesis. Perhaps it was the last judgment of some inhabited world, **perhaps a too successful experiment in induced radioactivity** on the part of some of the dwellers there. And perhaps also these two hypotheses are one, and what we were watching that evening was the detonation of a world on which too many men came out to look at the stars when they should have been dancing.

J.B.S. Haldane --
recalling his observation of Nova Aquilae 1918

Novae: The Standard Model

- ❑ Luminosity corresponding to hydrostatic burning on a degenerate core of $1.2 M_{\odot}$ (Paczynski 1971) is:

$$L_{\text{Pacz}} = 6 \times 10^4 (M/M_{\odot} - 0.511) \approx 4 \times 10^4 L_{\odot}$$

- ❑ Eddington luminosity for electron scattering:

$$L_{\text{Edd}} \approx 4 \times 10^4 L_{\odot} (M/M_{\odot})$$

- ❑ Total binding energy of an envelope of $2 \times 10^{-5} M_{\odot}$:

$$GMM_{\text{env}}/R \approx 1.6 \times 10^{46} \text{ erg}$$

- ❑ Kinetic energy of the ejecta:

$$E_{\text{KE}} \approx 4 \times 10^{44} \text{ erg} (M_{\text{ej}}/10^{-5} M_{\odot}) (v_{\text{ej}}/10^8 \text{ cm s}^{-1})^2$$

Novae: The Thermonuclear Model

- ❑ Standard Model: TNR's in accreted hydrogen-rich envelopes on white dwarfs in close binaries.
- ❑ Runaway conditions achieved at base of envelope, e.g.: $P_{\text{critical}} \approx 10^{19-20} \text{ dyne cm}^{-2} \Rightarrow \text{RUNAWAY}$
- ❑ Typical characteristics of novae in outburst include: $M_{\text{wd}} \sim 1.2 M_{\odot}$; $M_{\text{env}} \approx 10^{-5} M_{\odot}$, $dM/dt \approx 10^{-9} M_{\odot} \text{ yr}^{-1}$
- ❑ Rapid rise to maximum $T_{\text{max}} \sim 200\text{-}350 \text{ million } ^{\circ}\text{K}$
- ❑ Long term evolution at $\approx$ constant luminosity $10^4 L_{\odot}$

Stages of a Nova Outburst

- ❑ Accretion of mass onto the white dwarf yields degenerate runaway conditions at the base of the accreted H envelope.
 - ❑ $P_{\text{critical}} \approx \text{few} \times 10^{19} \text{ dyne cm}^{-2} \Rightarrow \text{RUNAWAY}$
- ❑ Peak temperatures achieved in runaway typically reach values $\sim 200\text{-}300 \text{ million } ^{\circ}\text{K}$, consistent with the operation of the hot hydrogen burning sequences.
- ❑ Immediately following runaway, a convective region develops and expands to comprise the entire envelope, carrying an $\approx$ Eddington luminosity pulse to the surface.
- ❑ Following a brief ($\approx$ days) phase of burning at high luminosity the subsequent evolution continues at approximately constant bolometric luminosity through the exhaustion of the nuclear fuel- via some combination nuclear burning, wind mass loss, and 'common envelope-driven' mass loss.

Nova Evolution relative to Planetary Nebulae Central Stars

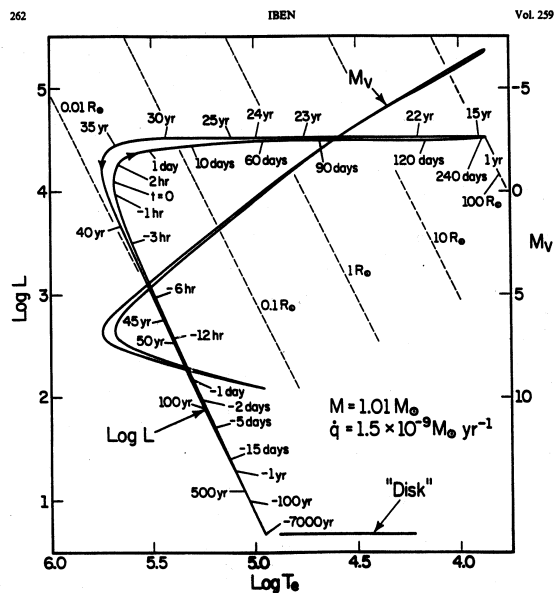


FIG. 21.—Same as Fig. 15, except for the time period about the third hydrogen-burning instability when accretion rate is $1.5 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$

Novae: The Last Three Minutes

- ❑ Enrichments in CNO elements are indeed required to power the most energetic novae.
- ❑ Once the temperature in the runaway exceeds ~ 80 million K, the rate of energy generation is limited by the rates of weak interactions ($\tau(^{15}\text{O}) = 176$ seconds).

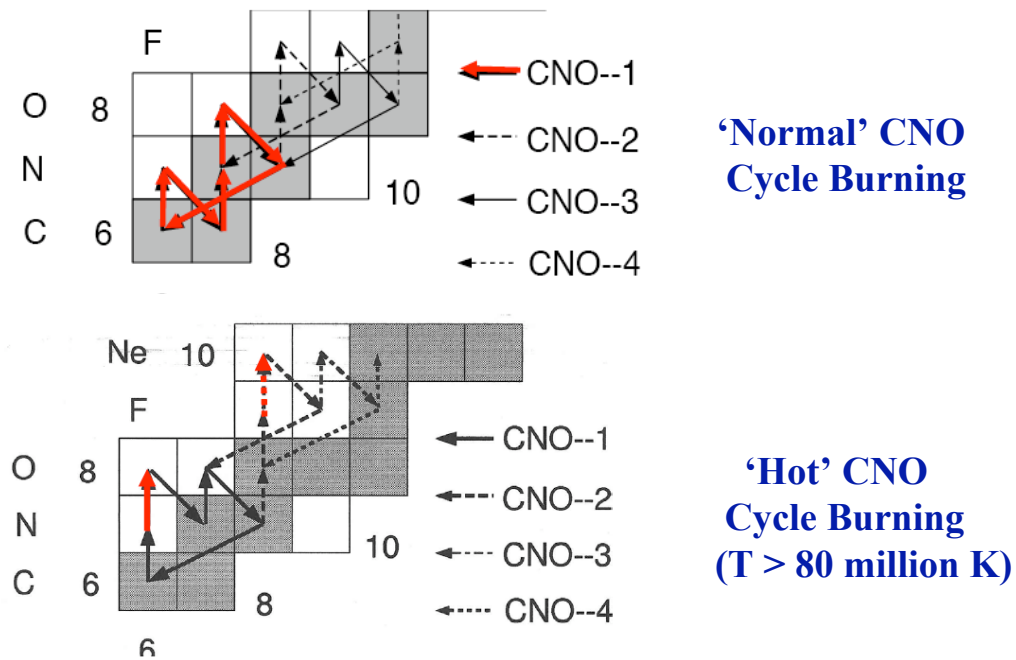


- ❑ The energy available on a dynamic timescale is then that arising from proton captures on existing CNO isotopes:

$$E_{\text{nuc}}/\rho \approx 2 \times 10^{15} \text{ erg g}^{-1} (n_{\text{cno}}/n_{\text{cno}}(\text{solar}))$$

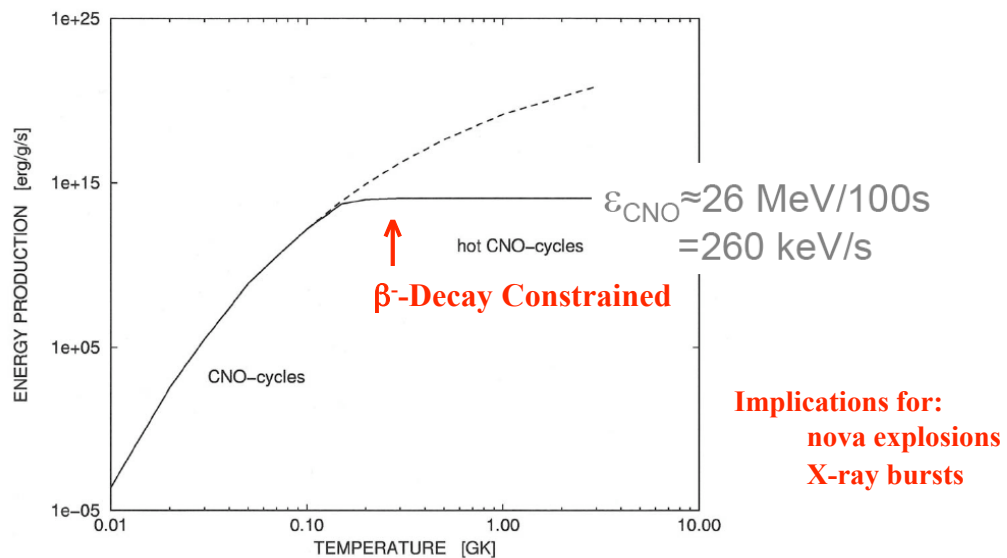
- ❑ Enrichments of CNO elements, such as are observed in nova ejecta, are thus demanded to achieve a rapid release of energy at a level approaching binding ($\approx 4 \times 10^{17} \text{ erg g}^{-1}$).

CNO Burning as a Function of Temperature

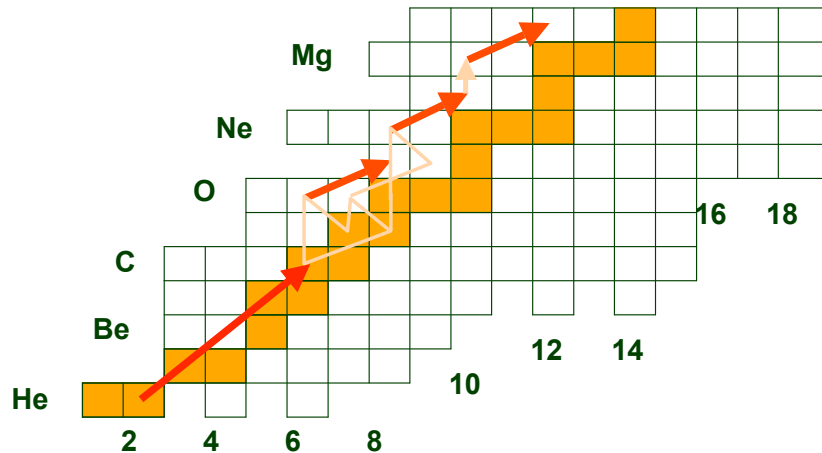


CNO Burning as a Function of Temperature

Impact on energy generation



Break-Out: $^{14}\text{O}(\alpha,p)$, $^{18}\text{Ne}(\alpha,p)$

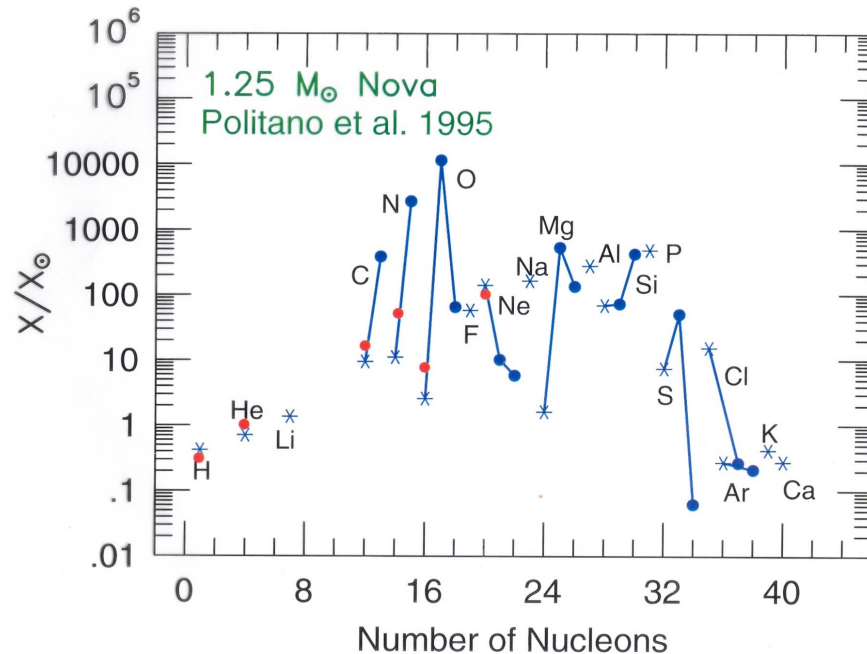


“Break-Out”: $T \approx 400$ million $^{\circ}\text{K}$

Nuclear Signatures of Nova Runaways

- ☐ Significant enrichments of CNO and ONe.
- ☐ Production of significant ^{13}C , ^{15}N , and ^{17}O from ^{13}N , ^{15}O , and ^{17}F .
- ☐ Peak temperatures ≤ 350 $^{\circ}\text{K} \Rightarrow$ **no breakout.**
- ☐ Gamma rays expected from ^{22}Na decay for novae at distances less than ≈ 0.5 kpc. Critical rates:
 $^{21}\text{Na}(\text{p},\gamma)^{22}\text{Mg}$ and $^{22}\text{Na}(\text{p},\gamma)^{23}\text{Mg}$
- ☐ Production of ^{26}Al at levels significantly below level observed in the ISM by Compton.
- ☐ Pre-solar grains from novae.

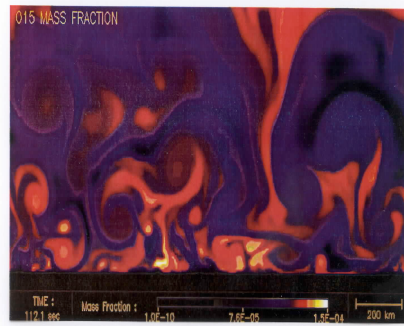
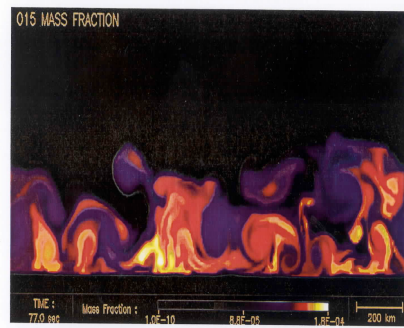
Nuclear Signatures of Nova Runaways



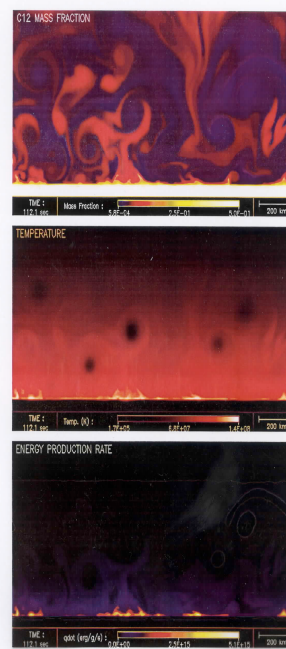
Challenges to Nova Theorists

- ☐ Outstanding problems now challenging nova theorists include:
 - ☐ identifying the mechanism by which nova envelopes are enriched in heavy elements.
 - ☐ modeling of the early luminosity history of novae in outburst.
 - ☐ understanding the apparent inconsistency of theory and observation with respect to the masses of nova ejecta.
 - ☐ clarifying the consequences of the phase of common envelope evolution that characterizes all novae at maximum light.
 - ☐ nucleosynthesis consequences (^{22}Na , ^{15}N , ^{17}O).

Convective Redistribution of Isotopes



The redistribution of ^{15}O over the envelope as a function of time. The spread of ^{15}O throughout the envelope, which serves to provide significant nuclear energy generation over the outer, cooler regions, is again evident. (Kereck, Hillebrandt, & Truran 1997)

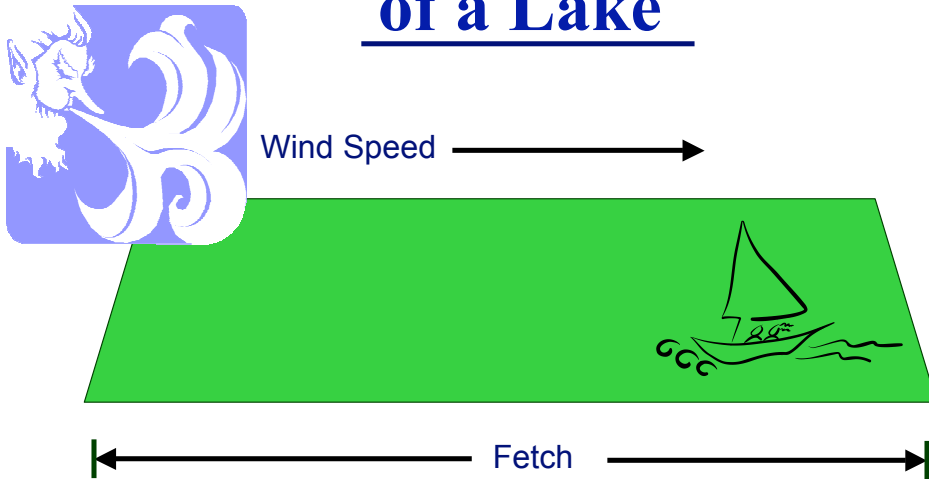


Dependence of the energy generation rate on temperature and ^{12}C abundance. Energy generation is strongly confined to the base of the burning region, at which point the ^{12}C concentration is greatest. (Kereck, Hillebrandt, & Truran 1997)

Gravity Wave Mixing and Novae

- ❑ Researchers have recently identified and explored the consequences of a resonant interaction between large-scale shear flows in nova envelopes and interfacial gravity waves.
- ❑ From a suite of 2-d simulations, they obtained measures of the rate and extent of mixing as a function of velocity, and derived an expression for the rate of mass entrainment as a function of wind velocity and time.
- ❑ Representative 3-d simulations were performed to further reveal the characteristics of this mixing process and validate the 2-d runs.

Gravity Waves on the Surface of a Lake



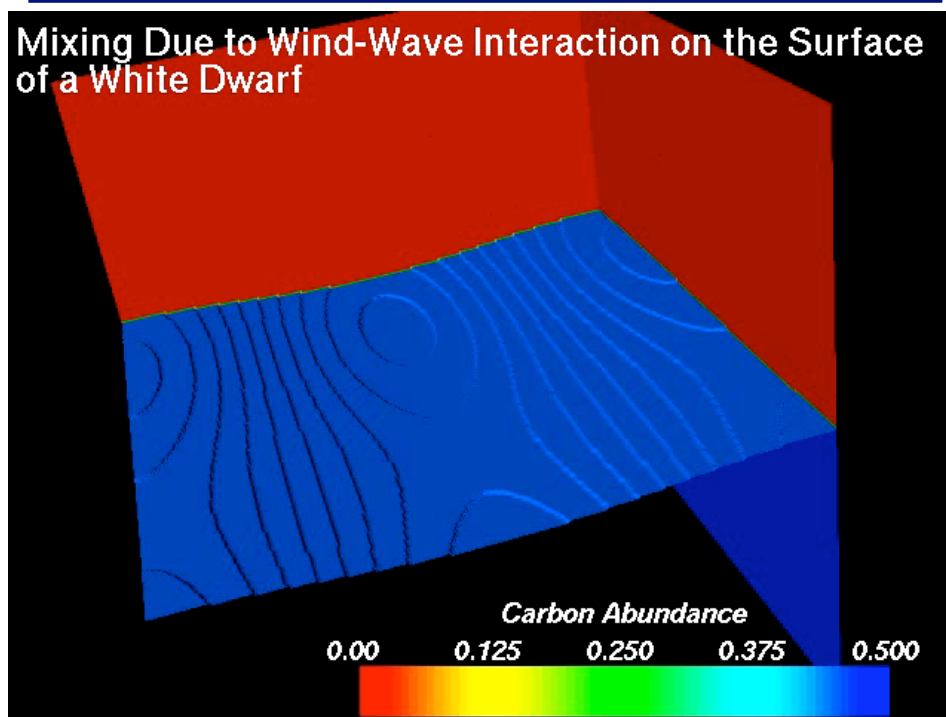
Gravity is the restoring force, hence “gravity waves.”



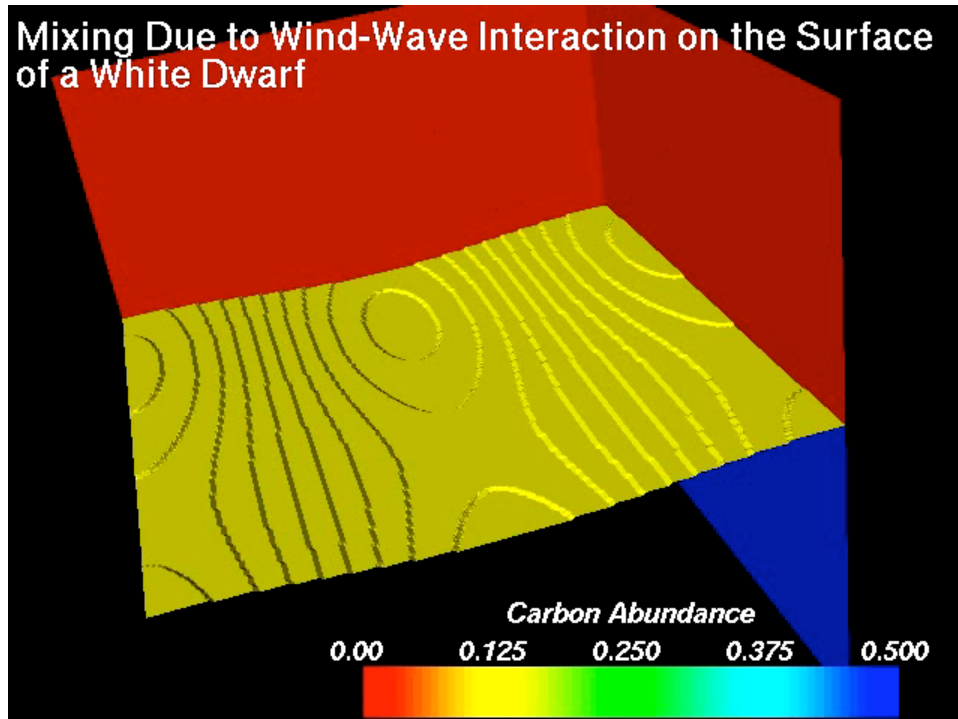
Wind Driven Mixing on White Dwarf



Mixing Due to Wind-Wave Interaction on the Surface
of a White Dwarf



Courtesy: ASC Flash Center, University of Chicago

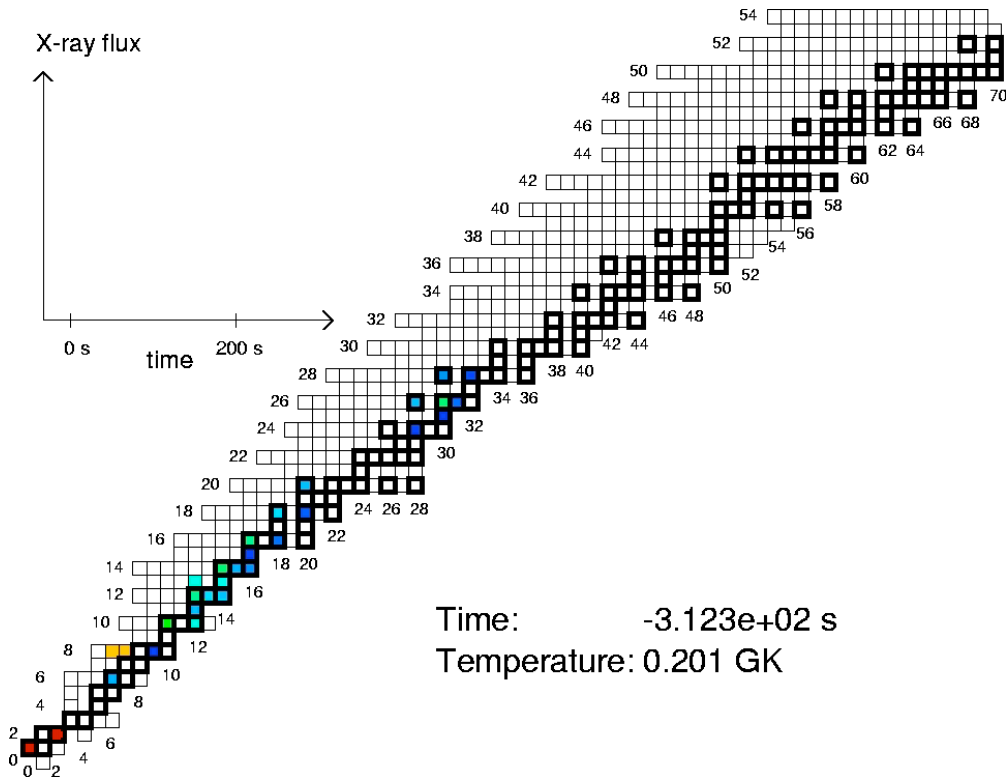


Courtesy: ASC Flash Center, University of Chicago

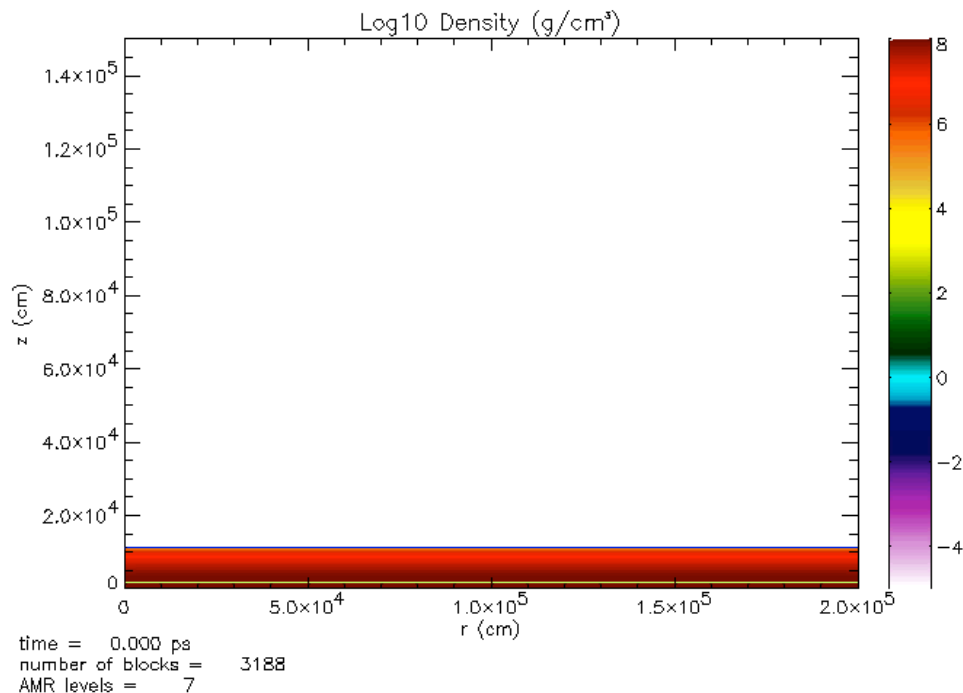
Concluding Remarks

- ❑ The thermonuclear runaway model for novae provides a textbook illustration of the manner in which nuclear physics acts to define astrophysical phenomenon.
- ❑ Constraints imposed by the beta-limited CNO reaction sequences are compensated by envelope enrichment in CNO elements to ~ 20 time solar.
- ❑ Shear/wind-driven gravity wave mixing provides an enrichment mechanism which is quantitatively in agreement with observations of nova ejecta.
- ❑ Detection of ^{22}Na gamma rays from novae would provide important constraints on runaway models.
- ❑ Many physics issues remain to be addressed.

rp-Process Nucleosynthesis: X-Ray Burst



Helium Detonation on Neutron Star



Courtesy: ASC Flash Center, University of Chicago

Zingale et al. (2001)