Sensitivity of Nova Bursts to the $^{14}N(p,\gamma)^{15}O$ Reaction Rate

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Classical Nova Background

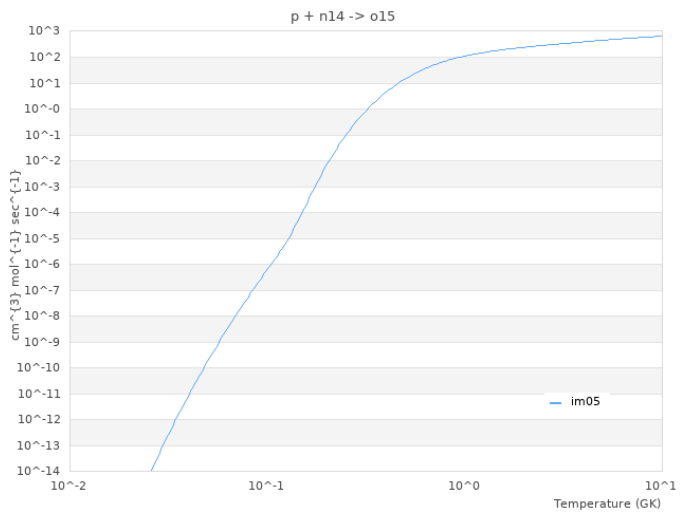
- White dwarf in binary system accretes hydrogen and CNO material from companion[1].
- Hydrogen shell builds on surface $\rightarrow$ compression $\rightarrow$ temperatures rises $\rightarrow$ CNO dominates at $\sim (1\text{–}1.5) \times 10^7\,\mathrm{K}$.
- Gradual hydrogen burning $\rightarrow$ temperature and density increases.
- Critical point $T \sim (2\text{–}10) \times 10^7\,\mathrm{K}$, thermonuclear runaway[2]

CNO Branch:

$$
\begin{aligned}
{}^{12}\mathrm{C}(p,\gamma) &\rightarrow {}^{13}\mathrm{N} \\
{}^{13}\mathrm{N}(\beta^+,\nu_e) &\rightarrow {}^{13}\mathrm{C} \\
{}^{13}\mathrm{C}(p,\gamma) &\rightarrow {}^{14}\mathrm{N} \\
{}^{14}\mathrm{N}(p,\gamma) &\rightarrow {}^{15}\mathrm{O} \\
{}^{15}\mathrm{O}(\beta^+,\nu_e) &\rightarrow {}^{15}\mathrm{N} \\
{}^{15}\mathrm{N}(p,\alpha) &\rightarrow {}^{12}\mathrm{C}
\end{aligned}
$$

$^{14}N(p,\gamma)^{15}O$ Reaction

- The $^{14}N(p,\gamma)^{15}O$ reaction is the **slowest reaction** and extremely temperature dependent.
- **Lower rate** $\rightarrow$ slower energy buildup $\rightarrow$ delayed ignition and lower peak luminosity.
- **Higher rate** $\rightarrow$ faster CNO cycling $\rightarrow$ earlier, more violent thermonuclear runaway.



Original JINA Reaclib temperature dependence data for $^{14}N(p,\gamma)^{15}O$[3].

Custom Reaction Rate Setup

- Based on the MESA test suite case `wd_nova_burst`.
- Constructed custom rate tables[4]:
  - Created (T_8, rate) tables scaled by 0.01, 1.0, and 100.
  - Added custom files to MESA's `rate_tables/` directory.
- Ran nova simulations under identical initial conditions to isolate reaction rate effects.

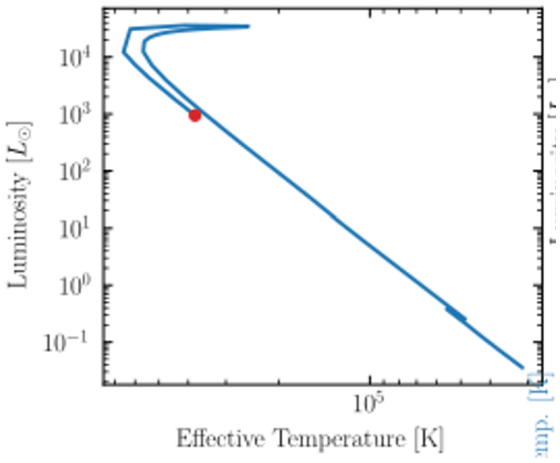
```
  GNU nano 7.2                                          rate_list.txt
! this is an example of a rates list file for use with mesa/rates
! the mesa/data/net_data/rates directory has sample rate files
! pairs of rate name and rate file
r_n14_pg_o15   'n14_pg_o14_custom_1p00.txt'
```

```
  GNU nano 7.2
24
  1.0    6.87000e-07
  1.5    1.12000e-04
  2.0    7.76000e-03
  3.0    5.99000e-01
  4.0    4.73000e+00
  5.0    1.52000e+01
  6.0    3.17000e+01
  7.0    5.19000e+01
  8.0    7.31000e+01
  9.0    9.39000e+01
 10.0    1.13000e+02
 15.0    1.89000e+02
 20.0    2.43000e+02
 25.0    2.88000e+02
 30.0    3.27000e+02
 35.0    3.64000e+02
 40.0    3.97000e+02
 45.0    4.28000e+02
 50.0    4.57000e+02
 60.0    5.08000e+02
 70.0    5.52000e+02
 80.0    5.91000e+02
 90.0    6.24000e+02
100.0    6.54000e+02
```

Right: Base data obtained from JINA Reaclib
Left: Custom rate file entry in `rate_list.txt`

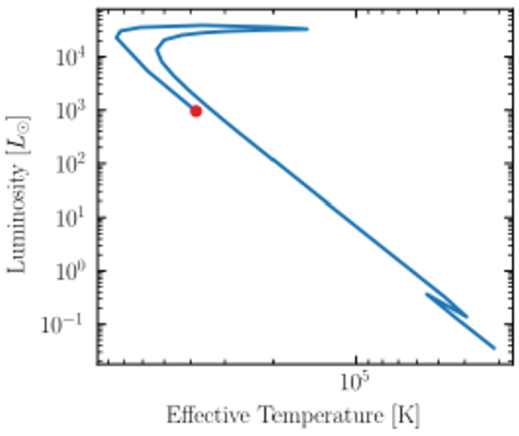
HR Diagrams for Different $^{14}N(p,\gamma)^{15}O$ Rates

0.01× Rate



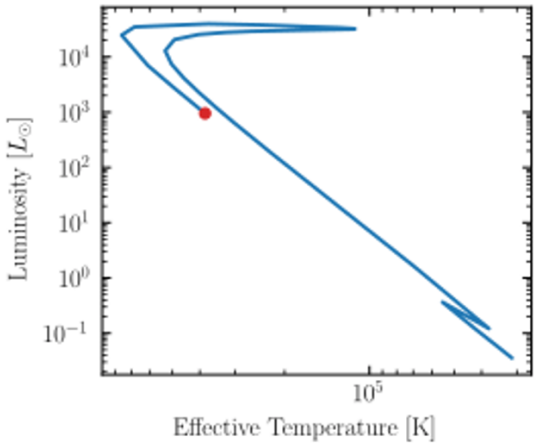
Weak TNR;
Barely expands;
Mostly steady burning.

1× Rate



Moderate heating;
typical nova behavior.

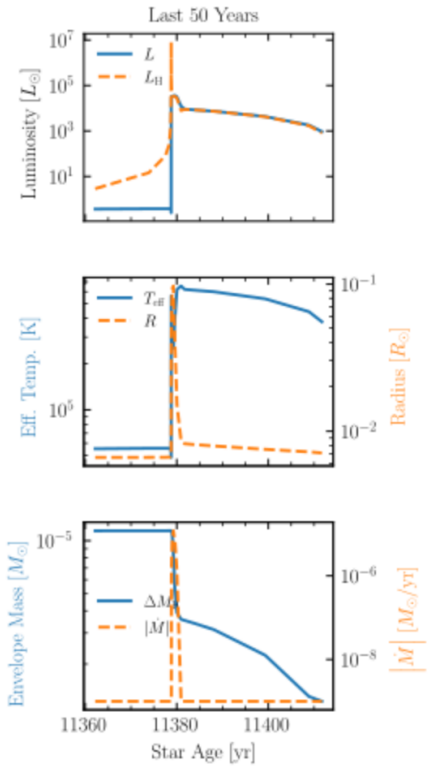
100× Rate



Violent TNR;
Rapid expansion;
Strong cooling.

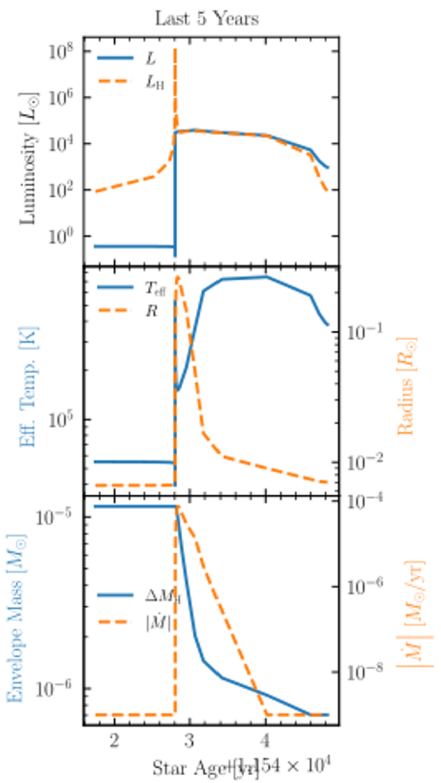
Luminosity Diagrams for Different $^{14}N(p,\gamma)^{15}O$ Rates

0.01× Rate



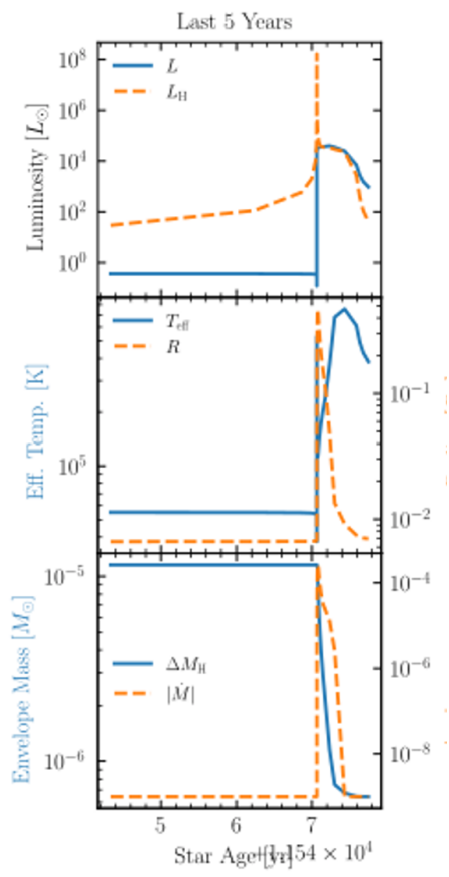
Ignites 67% earlier; very slow cooling

1× Rate



Clear rise in L_H; controlled TNR.

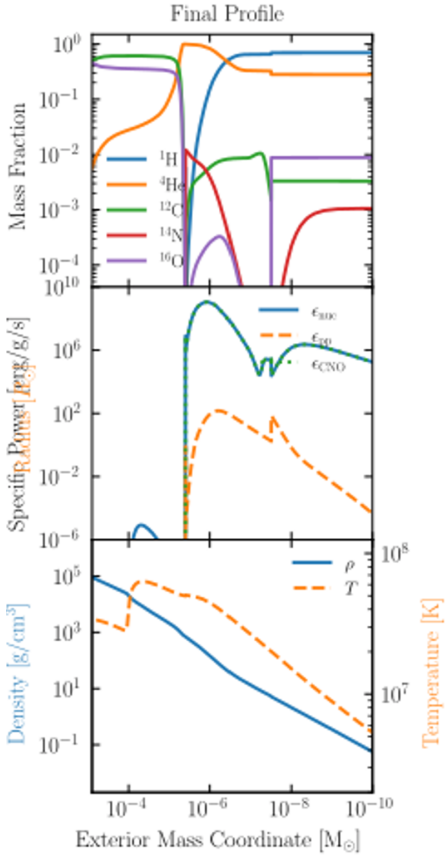
100× Rate



Ignites 133% later; explosive TNR.

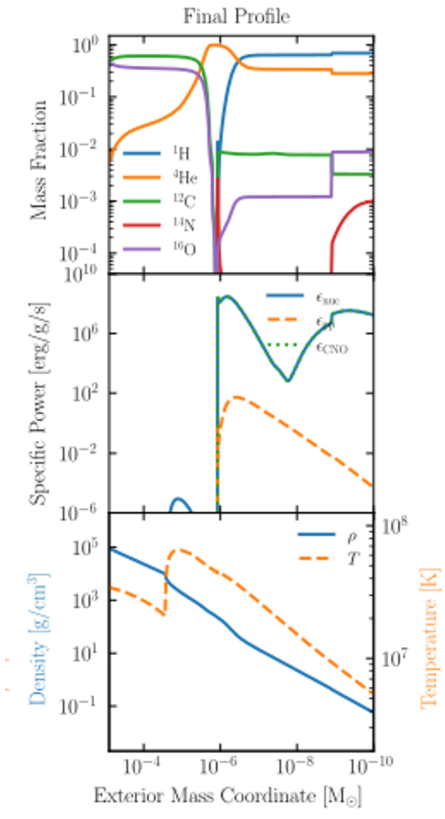
Energy Generation for Different $^{14}N(p,\gamma)^{15}O$ Rates

0.01× Rate



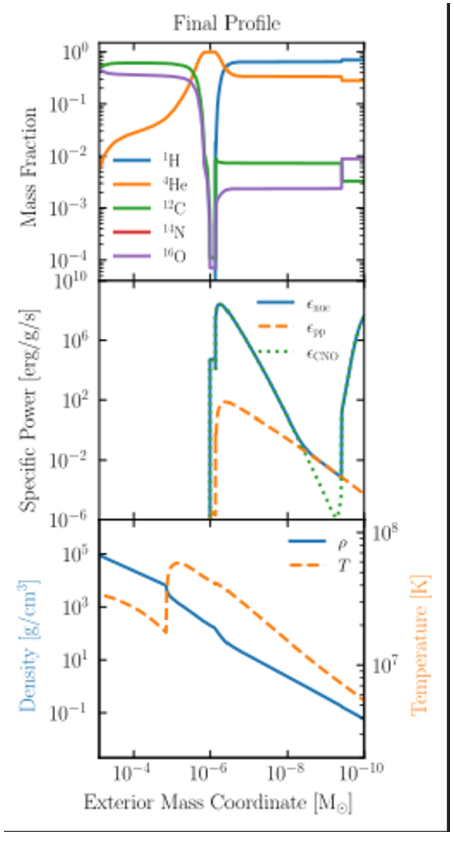
CNO cycle nearly inactive; pp-chain dominates.

1× Rate



Stable CNO burning; standard nova ignition.

100× Rate



Strong CNO spike; pp–CNO transition visible.

References and Acknowledgments

References

1. Chen et al., "Enhanced S-factor for the ^{14}N(p,)^{15}O reaction and its impact on the solar composition problem", *arXiv:2410.16086*.
2. José, J. & Shore, S. N. (2013), "Nuclear Thermometers for Classical Novae," *Astronomy & Astrophysics 559*, A7 (arXiv:1211.4794).
3. JINA REACLIB Database, "Rate details for ^{14}N(p,)^{15}O (im05)", available at `https://reaclib.jinaweb.org/n14(p,g)o15/im05/`.
4. Paxton et al., `MESA` Test Suite: "WD Nova Burst", `https://docs.mesastar.org/en/stable/test_suite/wd_nova_burst.html`.

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