WORSHOP ON NUCLEOSYNTHESIS

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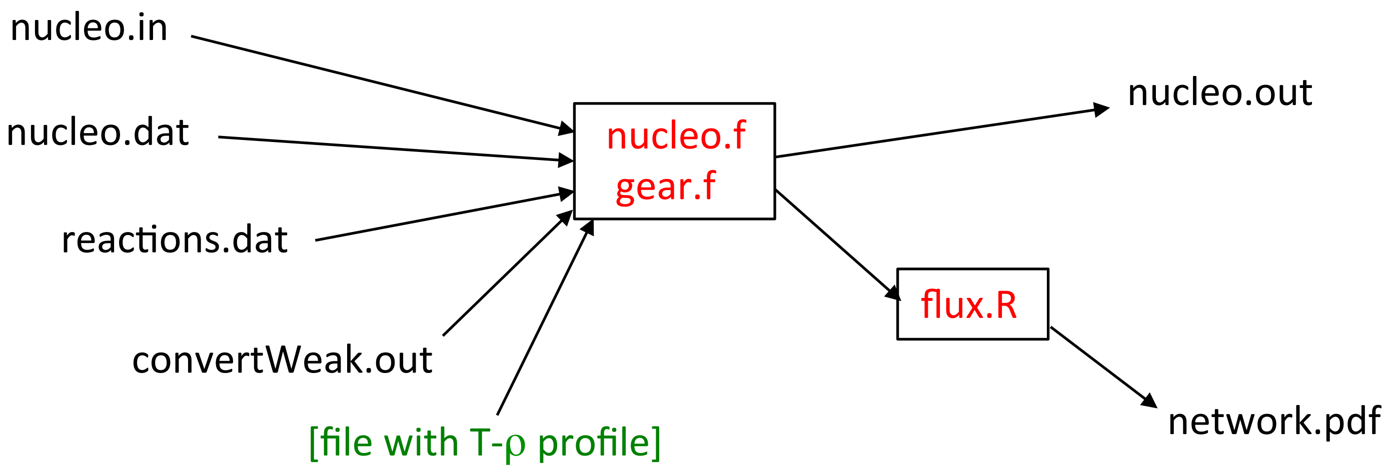
TUNL

COMPUTER CODES

you will need many files; copy the entire folder; compile everything by typing make in the terminal



nucleo.in

nucleo.dat

reactions.dat

convertWeak.out

[file with T-ρ profile]

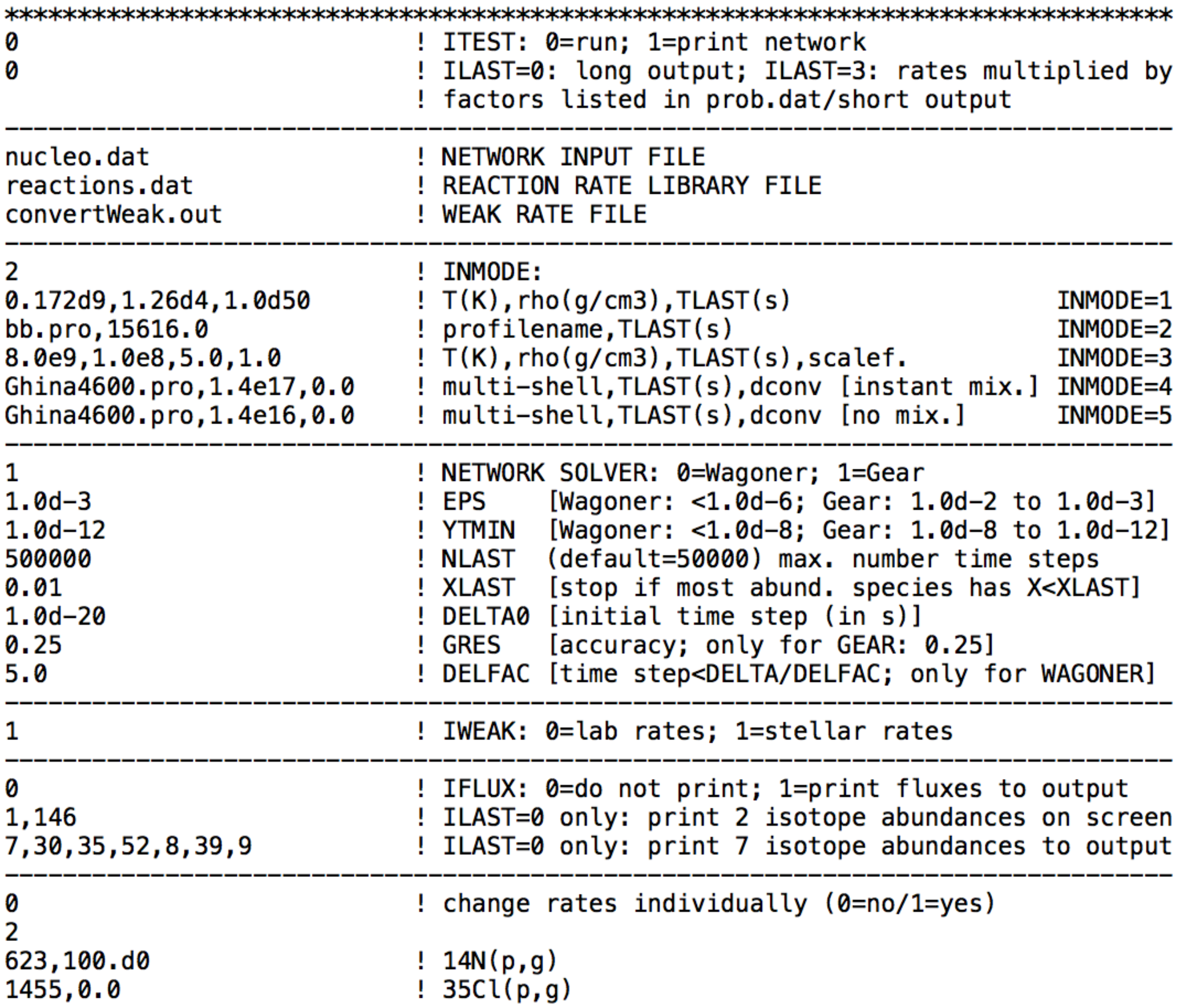
nucleo.f
gear.f

nucleo.out

flux.R

network.pdf

BIG BANG NUCLEOSYNTHESIS

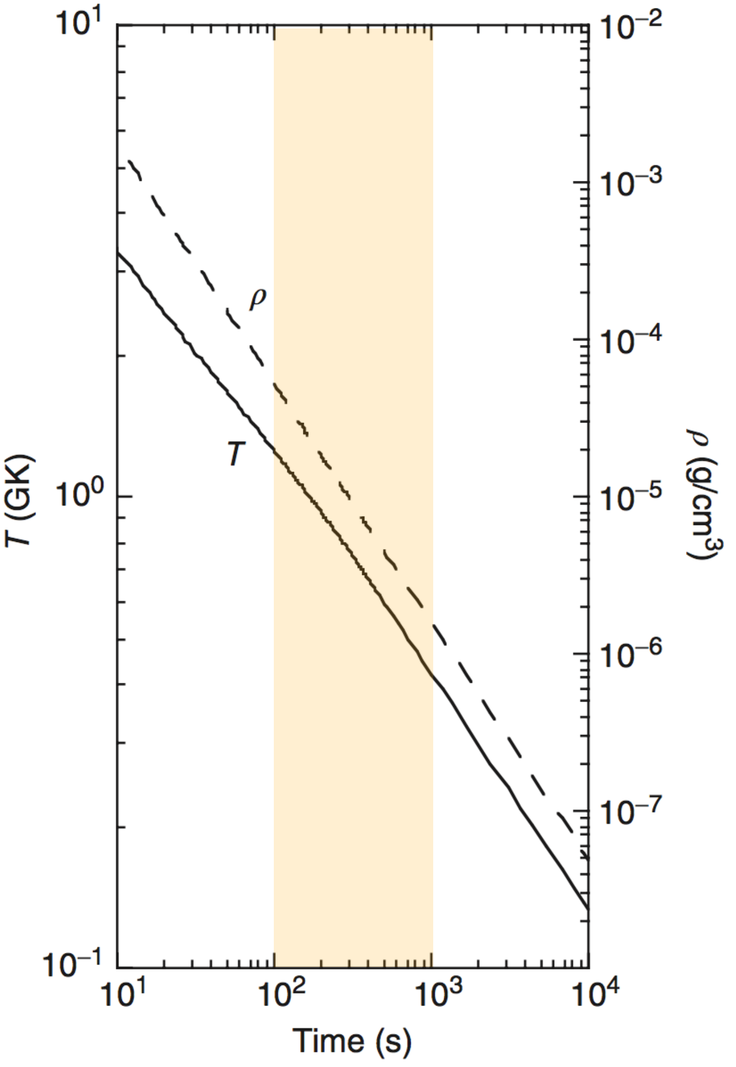


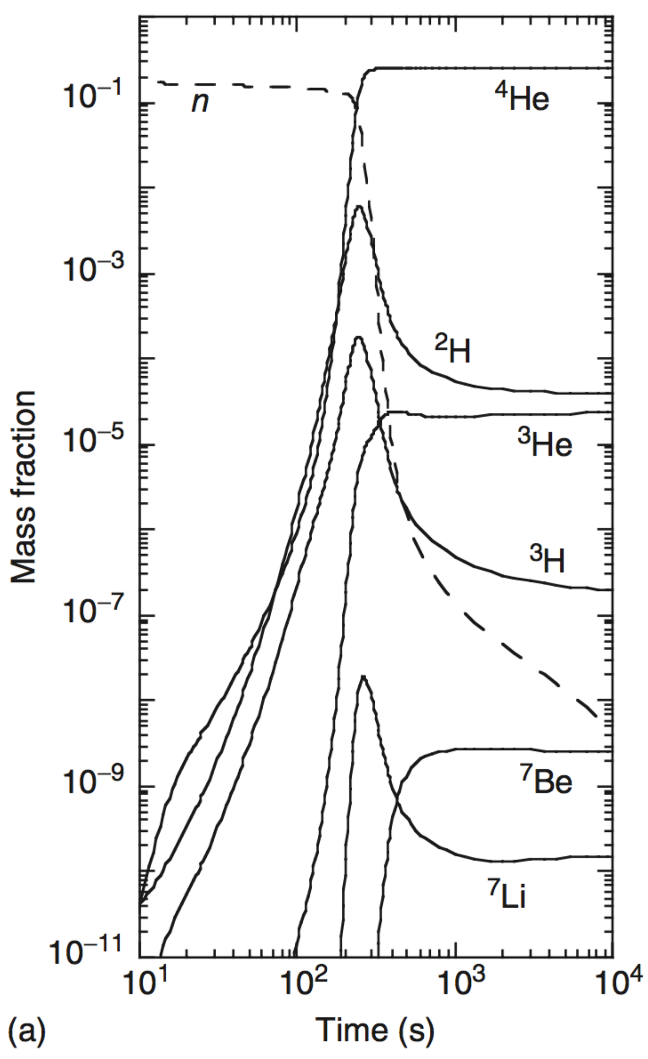
```
********************************************************************************
0                           ! ITEST: 0=run; 1=print network
0                           ! ILAST=0: long output; ILAST=3: rates multiplied by
                            ! factors listed in prob.dat/short output
--------------------------------------------------------------------------------
nucleo.dat                  ! NETWORK INPUT FILE
reactions.dat               ! REACTION RATE LIBRARY FILE
convertWeak.out             ! WEAK RATE FILE
--------------------------------------------------------------------------------
2                           ! INMODE:
0.172d9,1.26d4,1.0d50       ! T(K),rho(g/cm3),TLAST(s)                  INMODE=1
bb.pro,15616.0              ! profilename,TLAST(s)                      INMODE=2
8.0e9,1.0e8,5.0,1.0         ! T(K),rho(g/cm3),TLAST(s),scalef.          INMODE=3
Ghina4600.pro,1.4e17,0.0    ! multi-shell,TLAST(s),dconv [instant mix.] INMODE=4
Ghina4600.pro,1.4e16,0.0    ! multi-shell,TLAST(s),dconv [no mix.]      INMODE=5
--------------------------------------------------------------------------------
1                           ! NETWORK SOLVER: 0=Wagoner; 1=Gear
1.0d-3                      ! EPS    [Wagoner: <1.0d-6; Gear: 1.0d-2 to 1.0d-3]
1.0d-12                     ! YTMIN  [Wagoner: <1.0d-8; Gear: 1.0d-8 to 1.0d-12]
500000                      ! NLAST  (default=50000) max. number time steps
0.01                        ! XLAST  [stop if most abund. species has X<XLAST]
1.0d-20                     ! DELTA0 [initial time step (in s)]
0.25                        ! GRES   [accuracy; only for GEAR: 0.25]
5.0                         ! DELFAC [time step<DELTA/DELFAC; only for WAGONER]
--------------------------------------------------------------------------------
1                           ! IWEAK: 0=lab rates; 1=stellar rates
--------------------------------------------------------------------------------
0                           ! IFLUX: 0=do not print; 1=print fluxes to output
1,146                       ! ILAST=0 only: print 2 isotope abundances on screen
7,30,35,52,8,39,9           ! ILAST=0 only: print 7 isotope abundances to output
--------------------------------------------------------------------------------
0                           ! change rates individually (0=no/1=yes)
2
623,100.d0                  ! 14N(p,g)
1455,0.0                    ! 35Cl(p,g)
```

contains initial
abundances for
big bang*

T-ρ profile and
running time
[until end]

* rename the file “nucleo_BB.dat” to “nucleo.dat”


10^{1}
10^{0}
10^{-1}
T (GK)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
ρ (g/cm^{3})
ρ
T
10^{1}
10^{2}
10^{3}
10^{4}
Time (s)


10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
Mass fraction
n
^{4}He
^{2}H
^{3}He
^{3}H
^{7}Be
^{7}Li
10^{1}
10^{2}
10^{3}
10^{4}
Time (s)
(a)

THINGS TO EXPLORE FOR BIG BANG NUCLEOSYNTHESIS:

1. run nucleo; run R script flux.R to produce flux graph

2. run finalAbund.R [plot of final mass fractions at the end of the calculation]

3. note the numerical values of final mass fractions [in nucleo.out] of n, p, d, ^{7}Li and ^{7}Be; how do these compare with observations in metal-poor stars:

   X_a=0.2486±0.0002
   D/H=$(2.8\pm0.2)\cdot10^{-5}$
   ^{7}Li/H=$(1\text{-}2)\cdot10^{-10}$

   $$X_i \equiv \frac{N_i M_i}{\rho N_A}$$

4. if you did the calculation right, then you should be looking at the "Lithium Problem", the most outstanding puzzle of Big Bang nucleosynthesis.

5. plot the abundance evolutions [mass fractions vs. time] for n, d, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li and ^{7}Be using isoAbund.f and isoABund.R. At what time interval does most of Big Bang nucleosynthesis occur? [to compile the first code, type: `gfortran isoAbund.f -o isoAbund`]

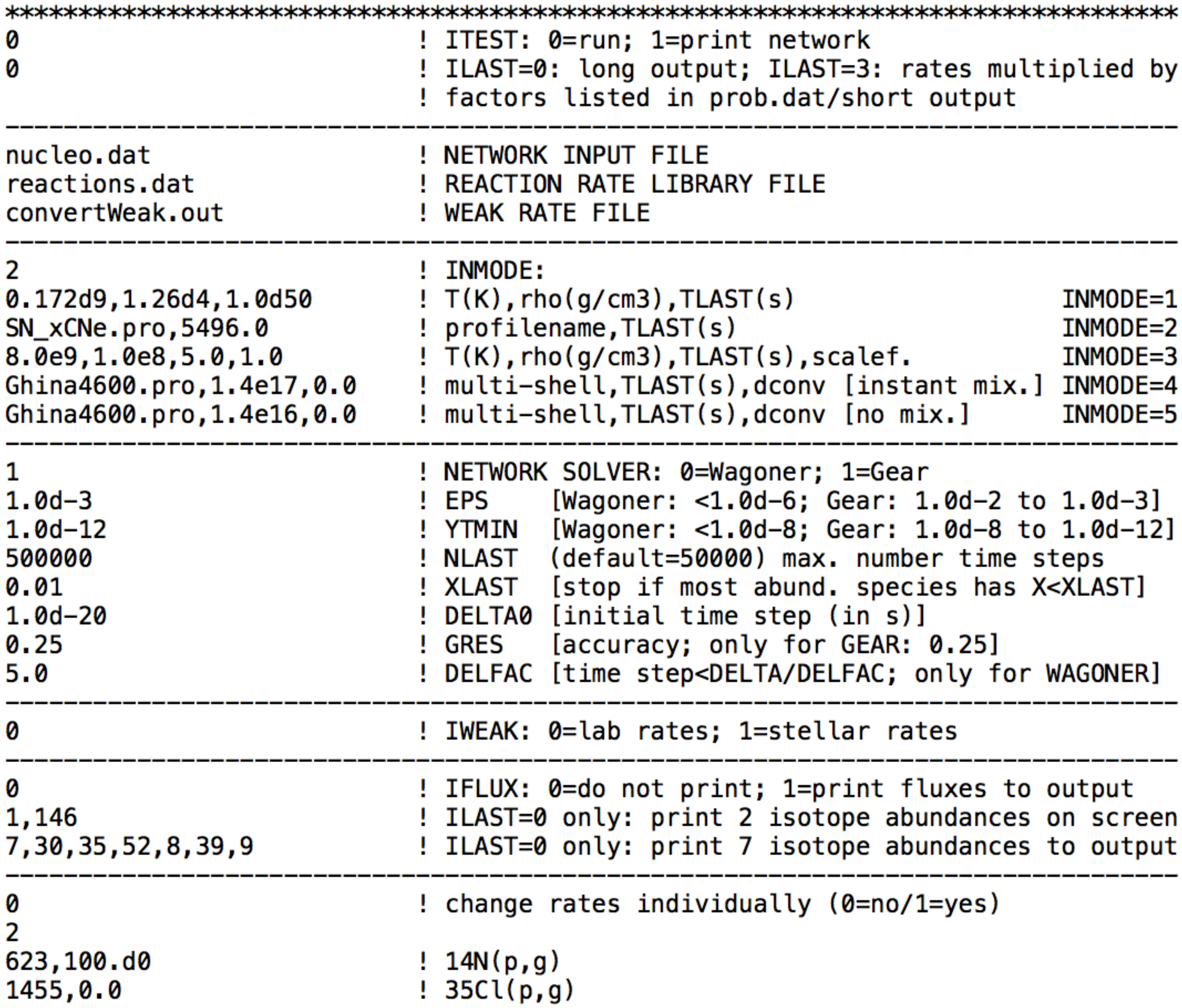
6. the species ^{6}Li, ^{9}Be and ^{10}B are always destroyed inside stars. What are their Big Bang abundances? What is their origin?

further reading: Coc, Goriely, Xu, Saimpert & Vangioni, ApJ 744, 158 (2012)

SUPERNOVA SHOCK NUCLEOSYNTHESIS

contains initial abundances for Supernova C/Ne layer* →

T-ρ profile and running time [until end] →



```
********************************************************************************
0                           ! ITEST: 0=run; 1=print network
0                           ! ILAST=0: long output; ILAST=3: rates multiplied by
                            ! factors listed in prob.dat/short output
--------------------------------------------------------------------------------
nucleo.dat                  ! NETWORK INPUT FILE
reactions.dat               ! REACTION RATE LIBRARY FILE
convertWeak.out             ! WEAK RATE FILE
--------------------------------------------------------------------------------
2                           ! INMODE:
0.172d9,1.26d4,1.0d50       ! T(K),rho(g/cm3),TLAST(s)                  INMODE=1
SN_xCNe.pro,5496.0          ! profilename,TLAST(s)                      INMODE=2
8.0e9,1.0e8,5.0,1.0         ! T(K),rho(g/cm3),TLAST(s),scalef.          INMODE=3
Ghina4600.pro,1.4e17,0.0    ! multi-shell,TLAST(s),dconv [instant mix.] INMODE=4
Ghina4600.pro,1.4e16,0.0    ! multi-shell,TLAST(s),dconv [no mix.]      INMODE=5
--------------------------------------------------------------------------------
1                           ! NETWORK SOLVER: 0=Wagoner; 1=Gear
1.0d-3                      ! EPS    [Wagoner: <1.0d-6; Gear: 1.0d-2 to 1.0d-3]
1.0d-12                     ! YTMIN  [Wagoner: <1.0d-8; Gear: 1.0d-8 to 1.0d-12]
500000                      ! NLAST  (default=50000) max. number time steps
0.01                        ! XLAST  [stop if most abund. species has X<XLAST]
1.0d-20                     ! DELTA0 [initial time step (in s)]
0.25                        ! GRES   [accuracy; only for GEAR: 0.25]
5.0                         ! DELFAC [time step<DELTA/DELFAC; only for WAGONER]
--------------------------------------------------------------------------------
0                           ! IWEAK: 0=lab rates; 1=stellar rates
--------------------------------------------------------------------------------
0                           ! IFLUX: 0=do not print; 1=print fluxes to output
1,146                       ! ILAST=0 only: print 2 isotope abundances on screen
7,30,35,52,8,39,9           ! ILAST=0 only: print 7 isotope abundances to output
--------------------------------------------------------------------------------
0                           ! change rates individually (0=no/1=yes)
2
623,100.d0                  ! 14N(p,g)
1455,0.0                    ! 35Cl(p,g)
```

* rename the file “nucleo_xCNe.dat” to “nucleo.dat”

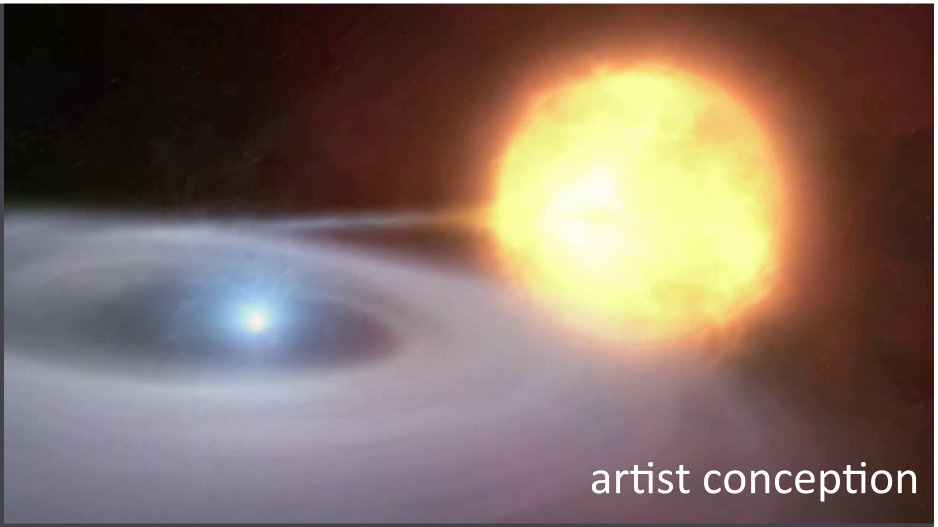
THINGS TO EXPLORE FOR SUPERNOVA SHOCK NUCLEOSYNTHESIS:

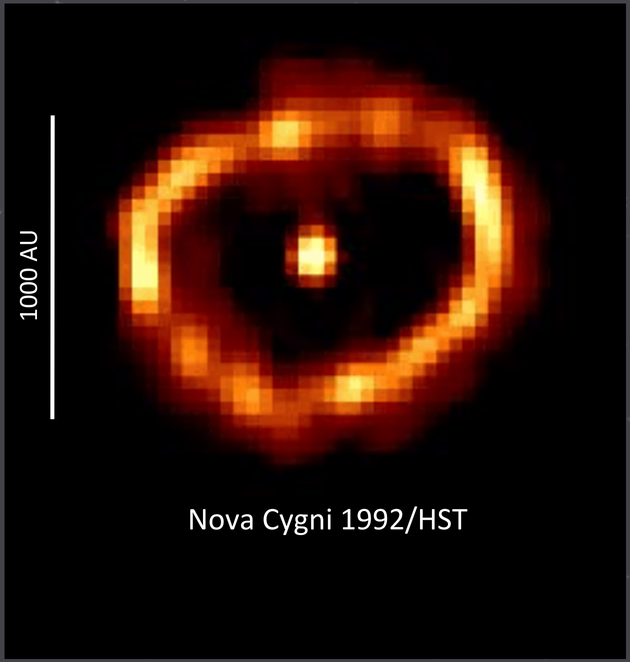
1. look at SN_xCNe.pro and notice T and ρ evolution; run R script flux.R to produce flux graph
2. run finalAbund.R to plot the final abundances; how do the final abundance change if you set IWEAK=0, i.e., if you use laboratory weak rates?
3. what are the most important reactions [maximum flow in flux.pdf] and most abundant nuclides [in finalAbund.pdf]?
4. plot the abundances ^{26}Al ["AL -6"] and ^{27}Al as a function of time: you have to first run isoAbund.f and then isoAbund.R; by what factor does the ^{26}Al abundance increase during the explosion?
5. repeat the network calculation, but this time multiply the rate of the ^{30}Si(p,γ)^{31}P reaction by a factor of 10. By how much does the final ^{26}Al abundance change? Can you explain why this reaction has an effect?

further reading: Iliadis, Champagne, Chieffi & Limongi, ApJS 193, 16 (2011)

CLASSICAL NOVAE

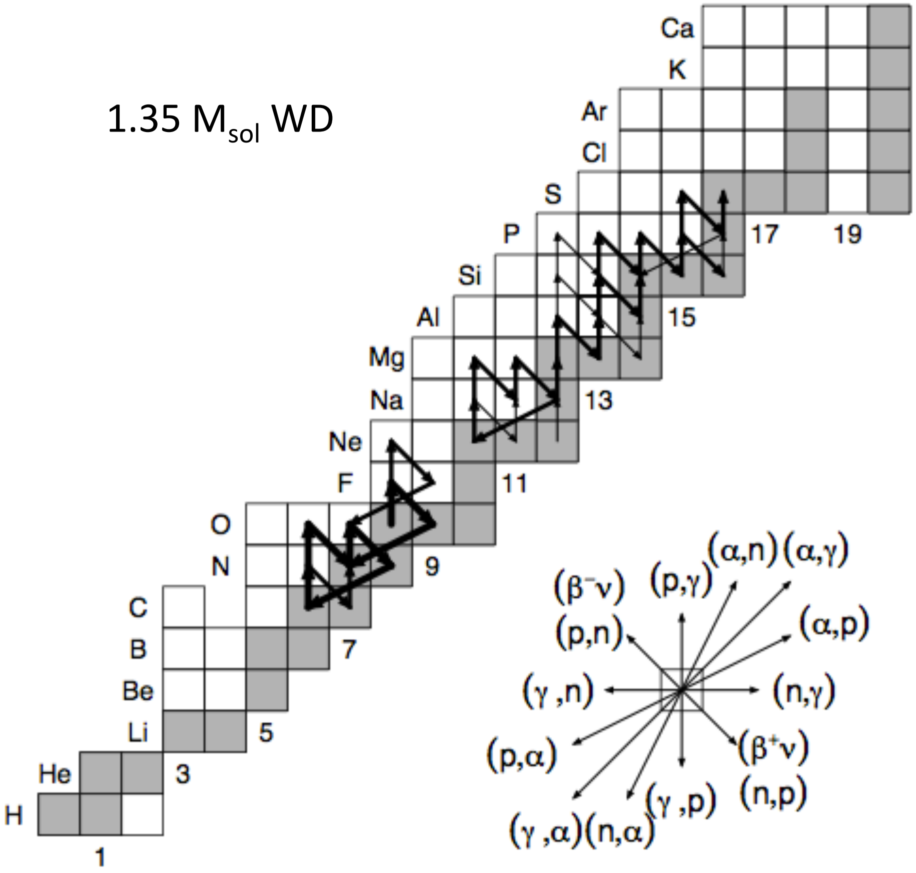
- are used as “standard candles” for cosmic distances
- are source of C, N, O isotopes in the galaxy
- are crucial for theories of stellar evolution
- are important for theories of stellar explosions


artist conception



Nova Cygni 1992/HST

1.35 M_{sol} WD



CLASSICAL NOVA NUCLEOSYNTHESIS

contains initial
abundances for
nova model*

T-ρ profile and
running time
[until end]

```
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                            ! factors listed in prob.dat/short output
--------------------------------------------------------------------------------
nucleo.dat                  ! NETWORK INPUT FILE
reactions.dat               ! REACTION RATE LIBRARY FILE
convertWeak.out             ! WEAK RATE FILE
--------------------------------------------------------------------------------
2                           ! INMODE:
0.172d9,1.26d4,1.0d50       ! T(K),rho(g/cm3),TLAST(s)                  INMODE=1
one_jo_125.pro,8.64e4       ! profilename,TLAST(s)                      INMODE=2
8.0e9,1.0e8,5.0,1.0         ! T(K),rho(g/cm3),TLAST(s),scalef.          INMODE=3
Ghina4600.pro,1.4e17,0.0    ! multi-shell,TLAST(s),dconv [instant mix.] INMODE=4
Ghina4600.pro,1.4e16,0.0    ! multi-shell,TLAST(s),dconv [no mix.]      INMODE=5
--------------------------------------------------------------------------------
1                           ! NETWORK SOLVER: 0=Wagoner; 1=Gear
1.0d-3                      ! EPS    [Wagoner: <1.0d-6; Gear: 1.0d-2 to 1.0d-3]
1.0d-12                     ! YTMIN  [Wagoner: <1.0d-8; Gear: 1.0d-8 to 1.0d-12]
500000                      ! NLAST  (default=50000) max. number time steps
0.01                        ! XLAST  [stop if most abund. species has X<XLAST]
1.0d-20                     ! DELTA0 [initial time step (in s)]
0.25                        ! GRES   [accuracy; only for GEAR: 0.25]
5.0                         ! DELFAC [time step<DELTA/DELFAC; only for WAGONER]
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--------------------------------------------------------------------------------
0                           ! change rates individually (0=no/1=yes)
2
623,100.d0                  ! 14N(p,g)
1455,0.0                    ! 35Cl(p,g)
```

* rename the file “nucleo_CN.dat” to “nucleo.dat”

THINGS TO EXPLORE FOR CLASSICAL NOVAE:

1. open one_jo_125.pro and notice T-ρ evolution; run nucleo; then run flux.R to produce flux graph

2. what are the most important reactions: (i) in the CNO region; (ii) in the mass region beyond CNO? Is there a reaction that transfers matter from the former to the latter mass region? What is the end point of the nucleosynthesis [i.e., highest-mass nuclide synthesized with significant abundance]?

3. run finalAbund.R; what is the most abundant nuclide, beside ^{1}H and ^{4}He, at the end of the calculation? [there is a reason why this phenomenon is called "neon nova"]

4. run isoAbund.f to extract the ^{20}Ne abundance evolution; then run isoAbund.R; you will see that the initial and final ^{20}Ne abundance is about the same; the observation of neon [mainly ^{20}Ne] in some nova ejecta was of paramount importance for models of stellar evolution, since it could be explained by dredge up of material from the underlying white dwarf. A significant neon abundance in white dwarfs immediately implies that the massive progenitor stars underwent core carbon burning [up to that point, all observed white dwarfs consisted of carbon and oxygen only – the ashes of helium burning in massive stars].

5. run nucleo by multiplying the rates of the following reactions:

^{17}O(p,γ)^{18}F:	factor 0.13
^{17}O(p,α)^{14}N:	factor 16.0

That's by how much the rates changed as a result of experiments at LENA/TUNL and Orsay/Paris. Run finalAbund.R and see by how much the abundances of nuclides in the CNO region change. These changes are important for oxygen isotopic ratios observed in presolar grains and for γ-ray astronomy.

further reading: Iliadis, Champagne, Jose, Starrfield & Tupper, ApJS 142, 105 (2002)