Supernova Nucleosynthesis

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Overview of Supernova Nucleosynthesis

o changes the content of the ISM

o produces heavy elements

o nuclear decay of ^{56}Co, produced during supernova nucleosynthesis, powers the light from supernova remnants

o observations of gamma rays emitted by supernova nucleosynthesis can provide important constraints on theoretical models
    o currently the deepest probe of supernova ejecta (gravitational waves would be deeper)

Radioactive Isotopes Synthesized in Supernovae

Isotope	Decay chain	Lifetime	Line energy (keV)
^{56}Ni	^{56}Ni $\rightarrow$ ^{56}Co	8.8d	158, 812, 750, 480
^{56}Co	^{56}Co $\rightarrow$ ^{56}Fe	111d	847, 1238
^{57}Ni	^{57}Ni $\rightarrow$ ^{57}Co $\rightarrow$ ^{57}Fe	(52h) 390d	122, 136
^{44}Ti	^{44}Ti $\rightarrow$ ^{44}Sc $\rightarrow$ ^{44}Ca	89yr (5.4h)	78, 68, 1157
^{26}Al	^{26}Al $\rightarrow$ ^{26}Mg	1.0×10^{6}yr	1809
^{60}Fe	^{60}Fe $\rightarrow$ ^{60}Co $\rightarrow$ ^{60}Ni	2.0×10^{6}yr (7.6yr)	1173, 1332

Hernanz, 2001

Core-Collapse Supernovae

o nucleosynthesis in core-collapse supernovae occurs in the form of explosive burning when the shock wave passes through layers of unburned material, igniting and accelerating it

o although reaction systems are complicated, yields can be predicted with use of some simplifying approximations:

o **Nuclear Statistical Equilibrium:** for sufficiently high temperature and density, strong and electromagnetic thermonuclear reaction rates are rapid enough to achieve equilibrium within the timescale of the supernova

o **Quasi-Equilibrium:** for temperatures in the range of 3-6 GK, although there is no global equilibrium, many nuclei are in local equilibrium with their neighbors
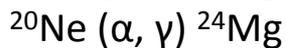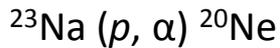
Carbon Burning

o calculations of explosive carbon burning for constant temperature done in Arnett and Truran 1969
    o took constant density of $5 \cdot 10^5$ g cm^{-3}
        o nucleosynthesis during carbon burning does not sensitively depend on the density
    o initial composition of equal parts ^{12}C and ^{16}O

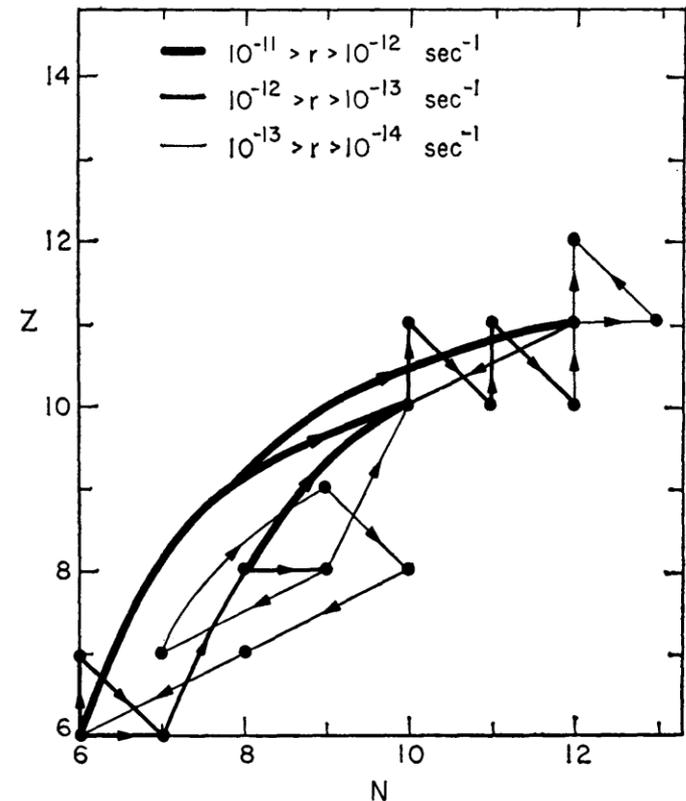o reactions in carbon burning that produce light particles:
    ^{12}C (^{12}C, α) ^{20}Ne
    ^{12}C (^{12}C, p) ^{23}Na
    ^{12}C (^{12}C, n) ^{23}Mg

o these light particles react much faster than the original ^{12}C + ^{12}C reaction
    o most significant reactions:

    ^{16}O (α, γ) ^{20}Ne
    ^{23}Na (p, α) ^{20}Ne
    ^{23}Na (p, γ) ^{24}Mg
    ^{20}Ne (α, γ) ^{24}Mg

Nuclear reaction flow diagram for carbon burning at T = $1.2 \cdot 10^9$ K with little carbon depletion

Carbon Burning
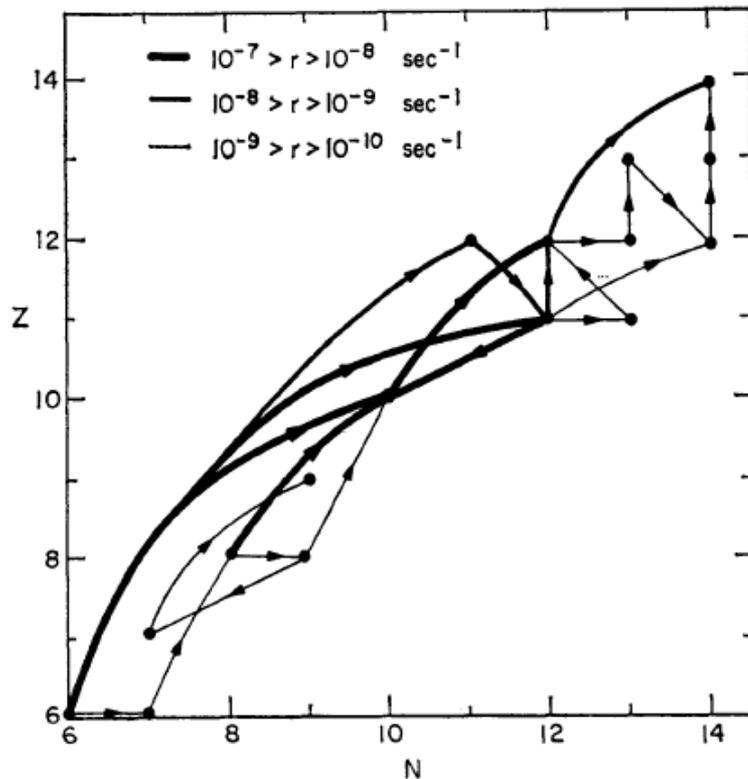
Nuclear reaction flow diagram for carbon burning at T = 1.2·10⁹ K at half carbon depletion

The graph legend shows:
- $10^{-7} > r > 10^{-8}$ sec^{-1}
- $10^{-8} > r > 10^{-9}$ sec^{-1}
- $10^{-9} > r > 10^{-10}$ sec^{-1}

The vertical axis is labeled Z, the horizontal axis is labeled N.

o neutron excess = (total neutrons – total protons)/total nucleons

o the number of free neutrons, protons, and alpha particles is small

o an increase in proton absorbers, particularly ^{23}Na, results in a decrease in protons and a constant number of alpha particles through the ^{23}Na (p, α) ^{20}Ne reaction

o neutron number is kept high by ^{12}C (^{12}C, n) ^{23}Mg

o when ^{12}C depletion becomes significant, the number of neutrons and alpha particles also begins to decrease
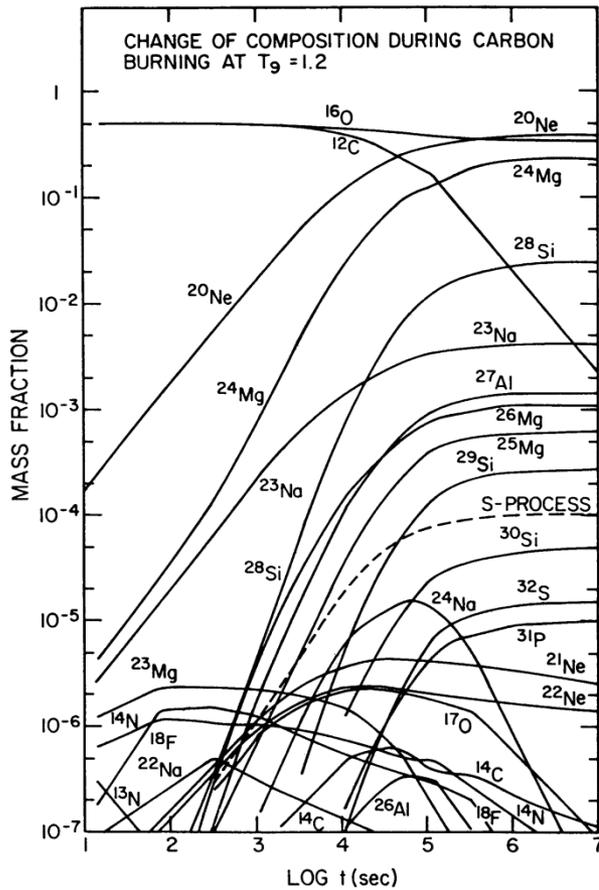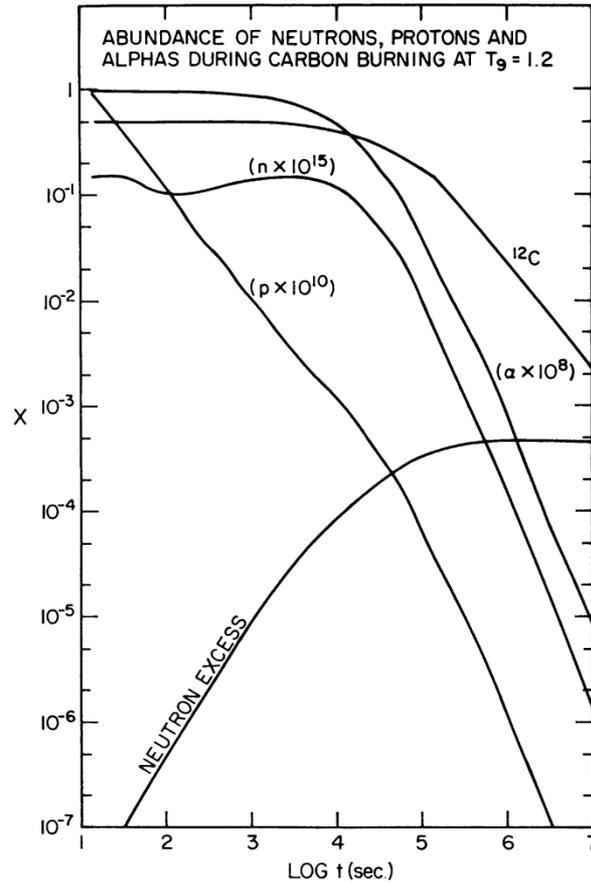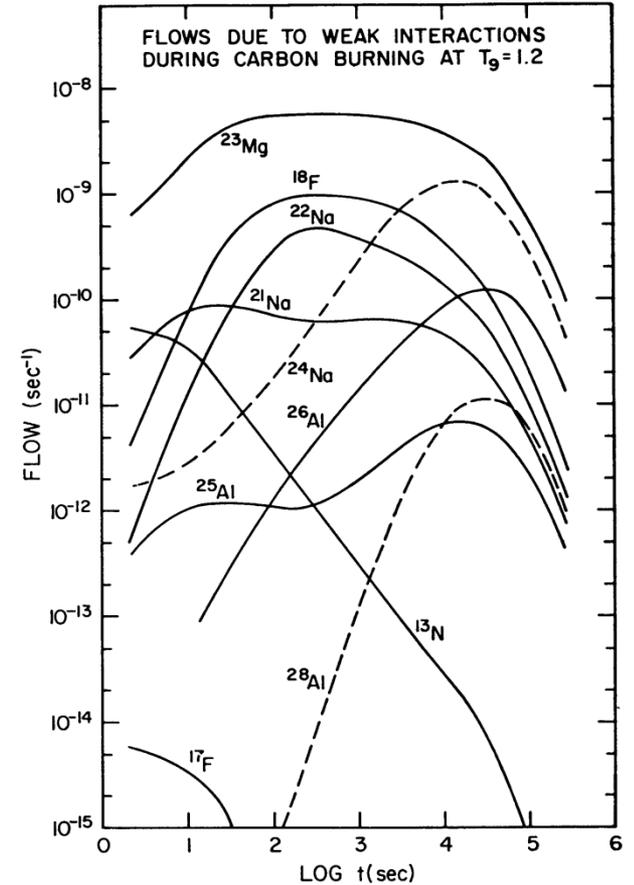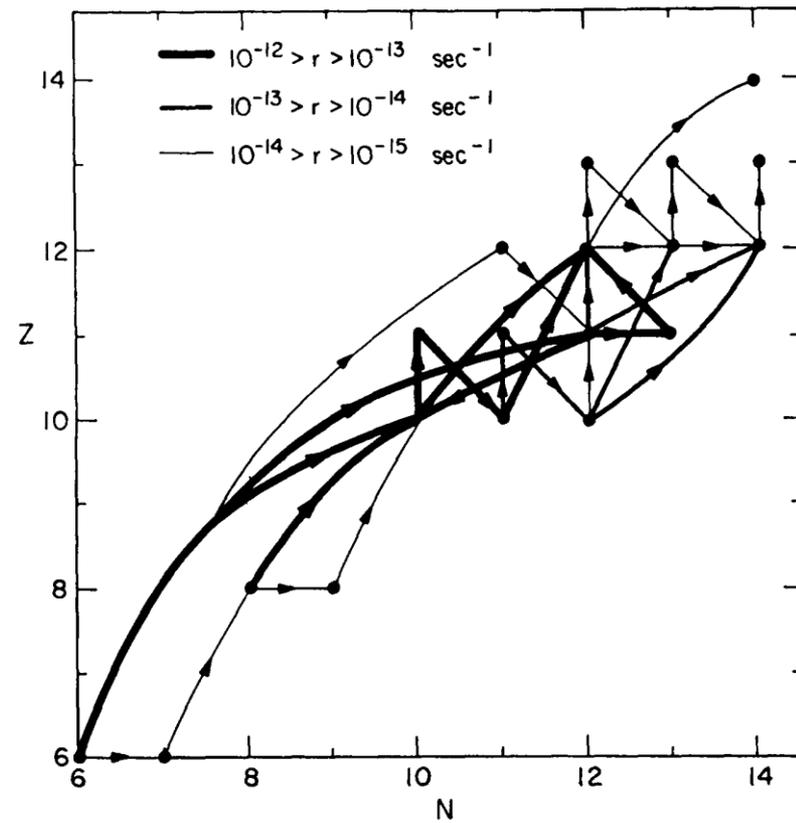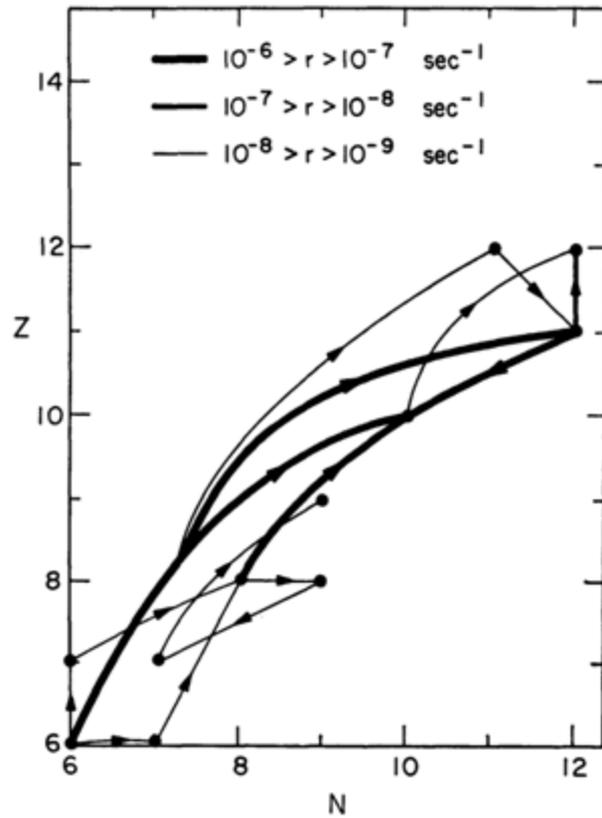
Carbon Burning

FIG. 4.—Variation of isotopic abundance by mass with time during carbon burning at $T_9 = 1.2$.

FIG. 5.—Variation of abundance by mass of neutrons, protons, and α-particles with time during carbon burning at $T_9 = 1.2$.

FIG. 6.—Variation of flows due to the weak interaction with time during carbon burning at $T_9 = 1.2$. *Solid lines*, β^+ decays; *dashed lines*, β^- decays.

Carbon Burning

o at T = $0.8 \cdot 10^9$ K, the gross behavior is similar to that at T = $1.2 \cdot 10^9$ K

Carbon Burning
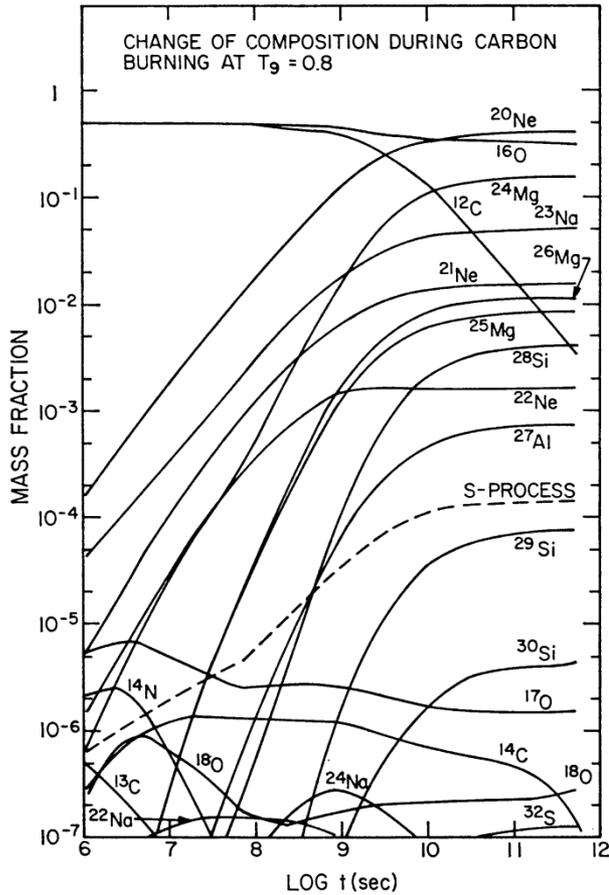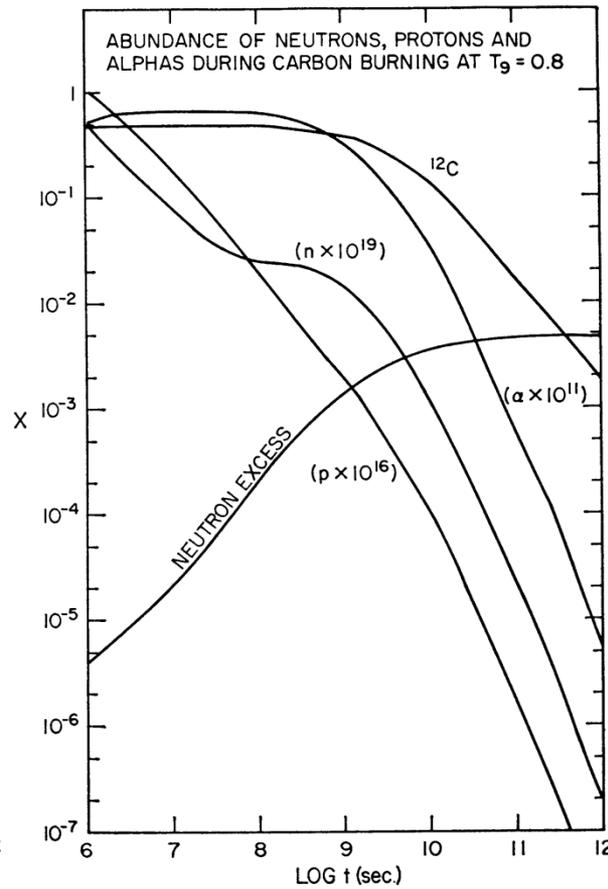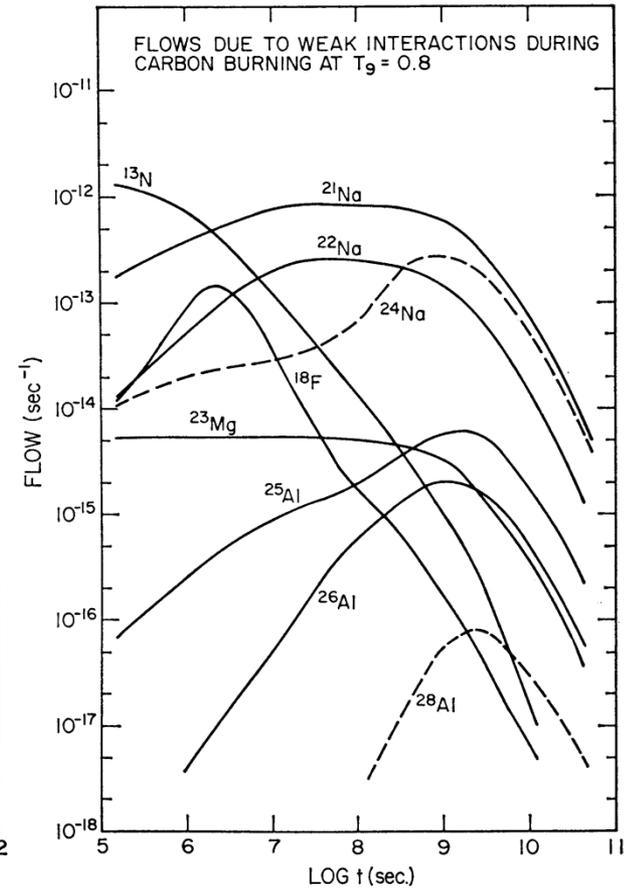

FIG. 9.—Variation of isotopic abundance by mass with time during carbon burning at $T_9 = 0.8$.

FIG. 10.—Variation of abundance by mass of neutrons, protons, and α-particles with time during carbon burning at $T_9 = 0.8$.

FIG. 11.—Variation of flows due to the weak interaction with time during carbon burning at $T_9 = 0.8$. *Solid lines,* β^+ decays; *dashed lines,* β^- decays.

Neon Burning

o neon and carbon burning have many similarities

o the main reaction is $^{20}Ne(\gamma, \alpha)^{16}O$
    o protons and neutrons are produced by (α, n) and (α, p) reactions

o behavior of abundances of neutrons, protons, and alpha particles is similar to that in carbon burning

o creates similar products to carbon burning, although ^{22}Ne and ^{23}Na are reduced in abundance

o carbon burning produces about three times more energy than neon burning

Oxygen Burning

o quasi-equilibrium behavior
  o less sensitive to reaction rates than carbon burning and more dependent on binding energies

o heavy elements (Z > 28) begin to photodissociate at the higher temperatures required for oxygen burning

o Woosley et al. 1973 did an analysis of explosive oxygen and silicon burning as an improvement on Truran and Arnett 1970, which was on explosive oxygen burning

  o initial composition for oxygen burning was about half ^{16}O and half ^{12}C
  o peak density was taken as $2 \cdot 10^5$ g cm^{-3}
  o peak temperature was taken as $3.6 \cdot 10^9$ K


Reaction Network
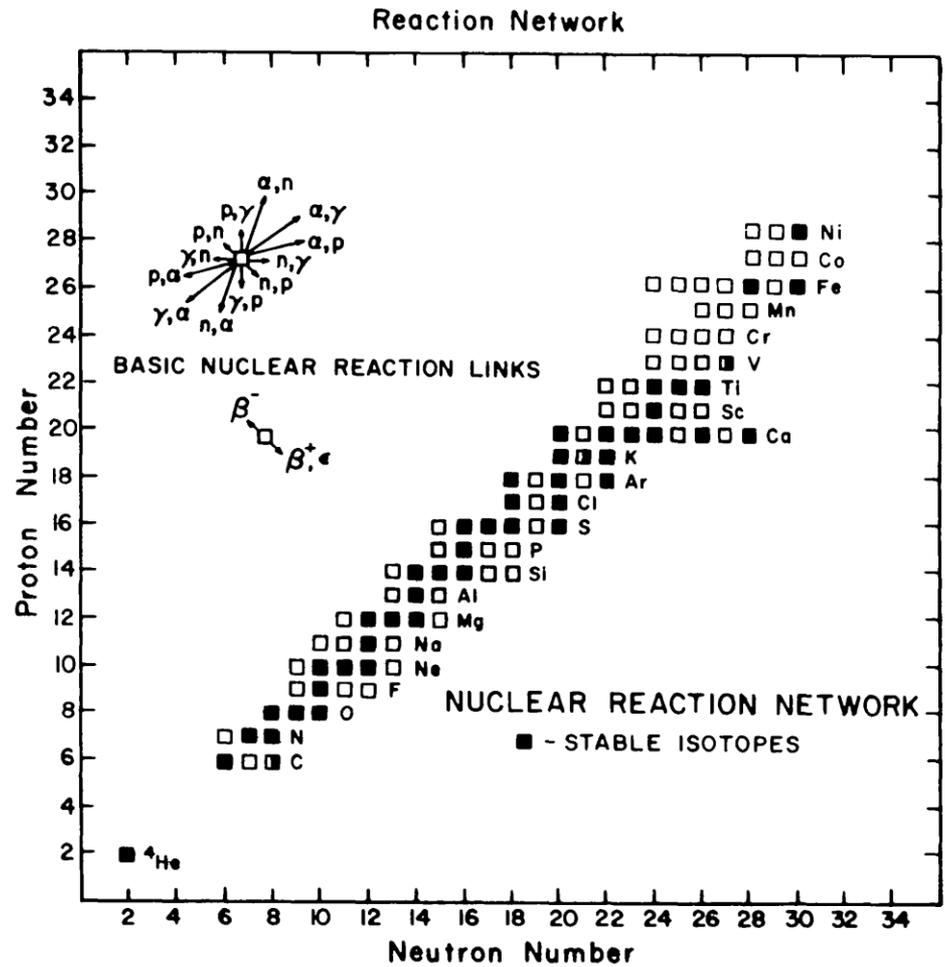
Oxygen Burning

o calculation by Woosley succeeded in reproducing major abundances from ^{28}Si to ^{42}Ca, as well as the correct solar abundances of ^{46}Ti and ^{50}Cr

o calculations also agreed well with Truran and Arnett

o driving reactions:
^{16}O (^{16}O, α) ^{28}Si
^{16}O (^{16}O, p) ^{31}P
^{16}O (^{16}O, n) ^{31}S
^{16}O (^{16}O, d) ^{30}P

^{16}O (γ, α) ^{12}C
o higher temperature and lower density favor this channel
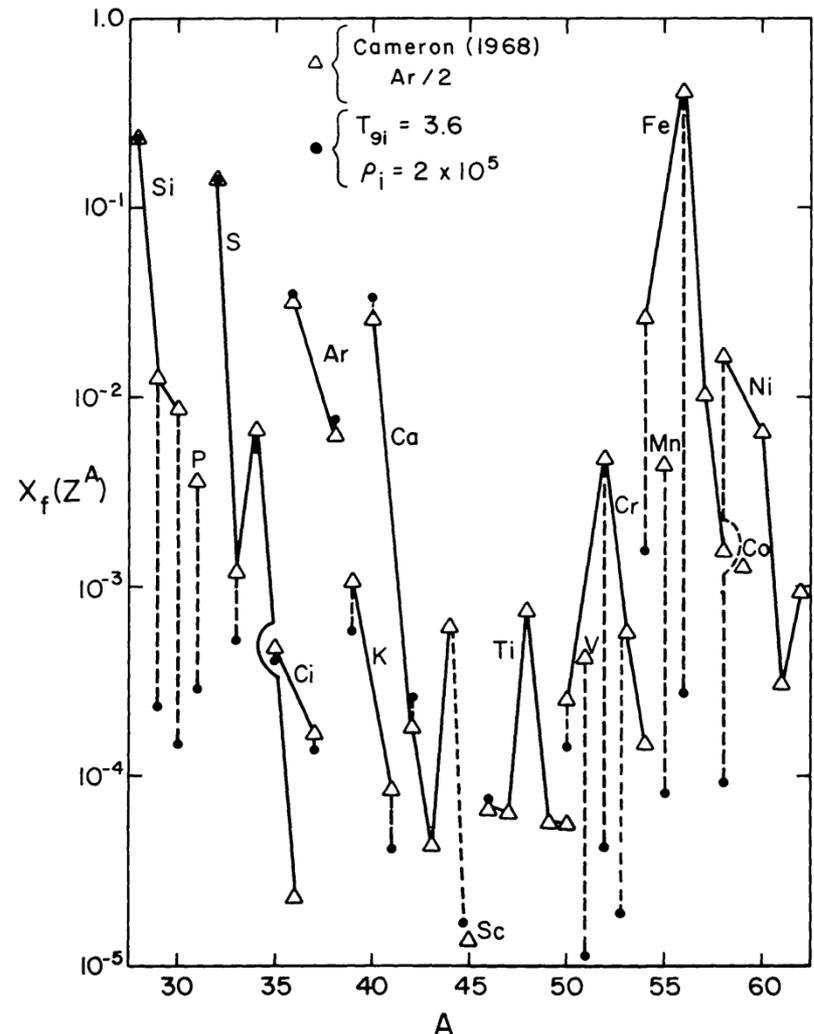
Silicon Burning

o silicon burning also shows quasi-equilibrium behavior

o if ^{16}O is depleted before freezeout, nuclear evolution will become characterized by photodisintegration rearrangement reactions

o produces a sizable amount of iron peak nuclei

o overall silicon burning process:
$^{28}Si\ (^{28}Si, 7\alpha)\ ^{56}Ni$

o Woosley et al. start with initial conditions of temperature $4.7 \cdot 10^9$ K and density $2 \cdot 10^5$ g cm^{-3}
   o continue the silicon burning where the oxygen burning ended
   o end up with good approximation of solar abundances

o extreme silicon burning will merge with the e-process and approach nuclear statistical equilibrium
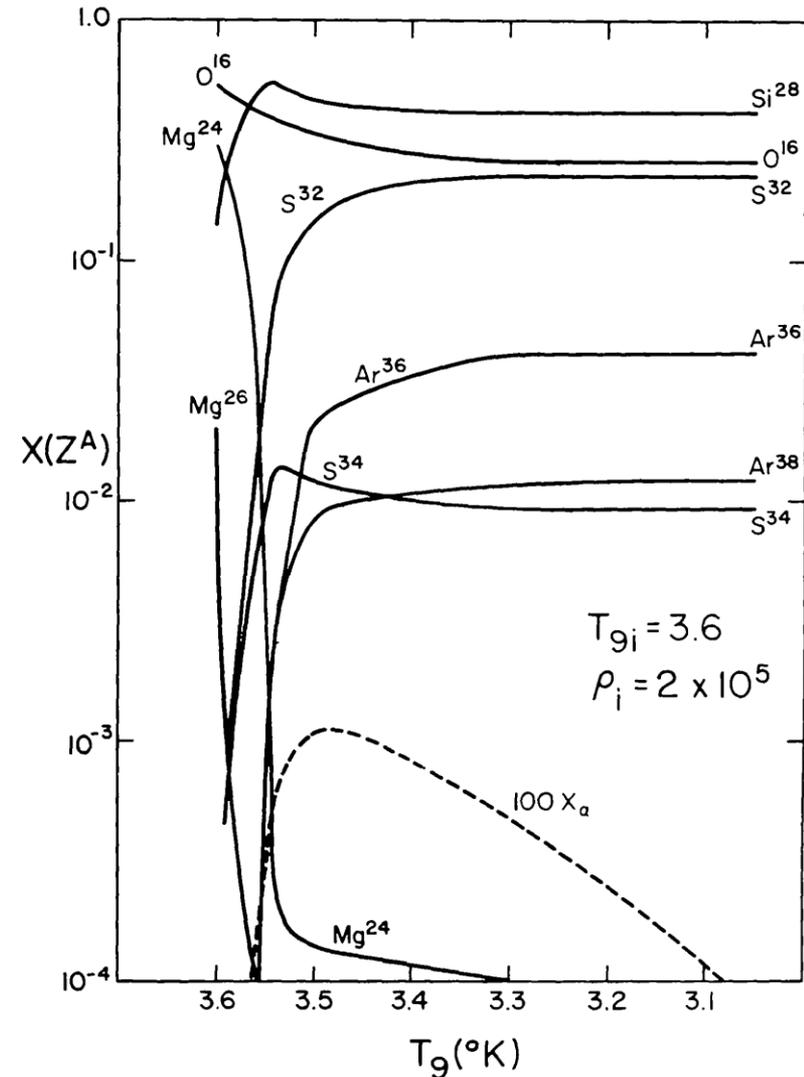
Observations of Nucleosynthesis in Core-Collapse Supernovae

o Type II supernova SN 1987A

  o light curve showed decline consistent with ^{56}Co

  o gamma ray lines from ^{56}Co detected at 847 and 1238 keV

  o confirmed by balloon-borne experiments

  o line profiles of ^{56}Co imply that the supernova explosion was not spherically symmetric

  o ^{57}Co decay detected

o type II supernova Cassiopeia A

  o obtained abundance estimates of S, Ar, Ca, Fe, and Ne, and upper limits for H, He, N, Mg, and C

  o displayed expected quasi-equilibrium pattern expected of oxygen burning
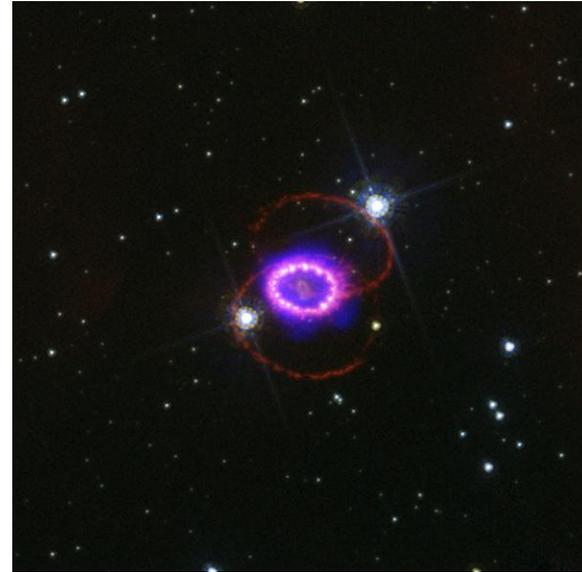
Credit: X-ray: NASA/CXC/PSU/ S.Park & D.Burrows.Optical: NASA/STScI/CfA/P. Challis
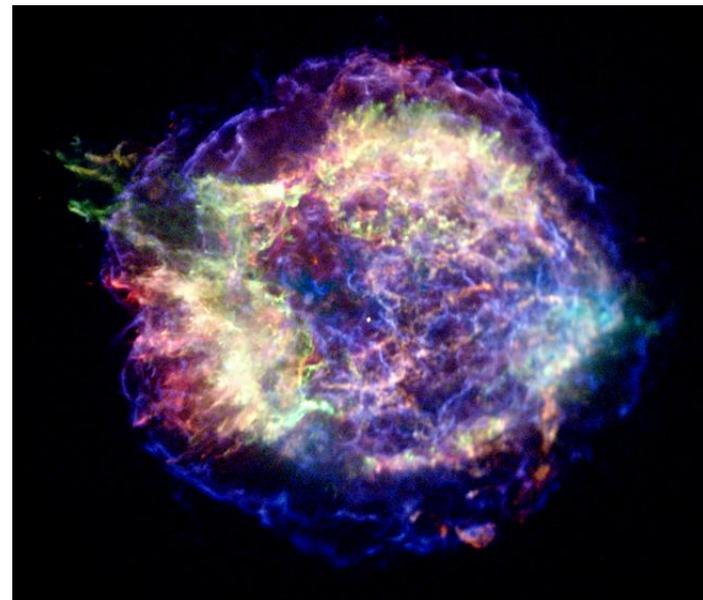
Credit: NASA/CXC/MIT/U Mass Amherst/ M.D.Stage et al.

Simulations of Core-Collapse Supernovae

o although we do not know the precise mechanism by which a core-collapse supernova proceeds, nucleosynthesis in a core collapse supernova can be computed by artificially simulating a supernova explosion

o injection of momentum through a piston that moves inward during the infall prior to the explosion and outward during the explosion

o does not allow material in the ejecta to slow down and collapse back onto the star

o underestimates fallback, leading to an overestimate of the amount of heavy elements, such as ^{56}Ni

o "thermal bomb" – injection of thermal energy into the Fe core in a way such that the ejecta attains a kinetic energy of ~10^{51} erg

o designed to incorporate the energy increase in the convective region

Thermonuclear Supernovae (SNIa)

o probable mechanism for SnIa: delayed detonation

    o burning is subsonic (deflagration) in the inner core where densities are large and supersonic (detonation) in the outer core
        o pure detonation at densities larger than ~10^7 g cm^{-3} would cause the entire star to be incinerated to Ni
        o deflagration overproduces some neutronized isotopes, such as ^{54}Fe, ^{54}Cr, and ^{58}Ni

    o ^{56}Ni lines (158, 750, 812 keV) prominent during first few days
        o 158 keV line is the most interesting to discriminate between models
            o almost undetectable in pure deflagration models
            o strong in pure detonation models

    o ratio between fluxes of ^{56}Co 847 keV line (200 days after maximum) and 158 keV line (at maximum)
        o provides information about the ratio between ^{56}Ni in the ejecta and the external layers

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