Carnegie Observatories Astrophysics Series, Vol. 4:
Origin and Evolution of the Elements, 2004
ed. A. McWilliam and M. Rauch (Cambridge: Cambridge Univ. Press)

Stellar Nucleosynthesis: A Status Report 2003

DAVID ARNETT
Steward Observatory, University of Arizona

1.1 Introduction

How well can we predict the production of nuclei during the evolution and death of a generation of stars? Although the basic framework for understanding the synthesis of nuclei by thermonuclear reactions in stars was established almost half a century ago (Burbidge et al. 1957, B^2FH; Cameron 1957), quantitative simulation of nucleosynthesis in a stellar model had to await for access to faster computers. The first nucleosynthesis computation in a stellar evolutionary sequence (using a reaction network of 23 nuclei including the iron peak), was done at Sir Fred Hoyle's Institute of Theoretical Astronomy (Arnett 1968). The computer resourses required were such as to insure that such computations were rare! Nonetheless, it uncovered the characteristic SiSArCa production in oxygen burning and the beginnings of core convergence due to neutrino cooling. We have now had 23 doublings (a factor of $\sim 10^7$) in computer power from Moore's Law, so that it is now possible to use larger networks and explore parameter space. In this review we will place recent computations in a historical context, with emphasis upon the challenges for the future as well as the successes of the present.

The pioneering work of the Burbidges, Fowler, Hoyle, and Cameron was stimulated by precise abundance data for the solar system just made available by Seuss & Urey (1956); similarly, modern nucleosynthesis theory is driven by increasingly precise data from cosmic rays, meteorites, and astronomical objects. With the advent of microanalysis of pre-solar grains, high-energy density lasers, 8-meter class ground-based telescopes, space-based multiple wavelength detectors, faster computers, and a wealth of nuclear physics data, theory is still driven by a strong and well-based empiricism.

1.2 Fundamentals

The solar system abundance pattern indicates that the values of several critical parameters are reproduced under stellar conditons. Theorists know that these constraints must be satisfied by any acceptable theory. The challenge presently confronting us is not whether or not we can reproduce the solar system pattern of isotopic abundances, but whether we can determine—uniquely—how nature did it.

1.2.1 Radiation Entropy

The vast difference between stellar nucleosynthesis and Big Bang nucleosynthesis is due to the very high entropy of the Big Bang, and the modest entropy of stars. The thermal energy of the Big Bang at the time of nucleosynthesis is dominated by black body photons

(Kolb & Turner 1990); the entropy of this radiation (per nucleon) is $S_\gamma/\Re = 4aT^3/3\rho\Re$ in Boltzmann units. Here T is the temperature, ρ the mass density, a the radiation constant, and $\Re$ the gas constant. This is simply related to the ratio of photon to baryon number by $n_\gamma/n_b = 0.2776 S_\gamma/\Re$. The ratio T^3/ρ also appears in a fundamental way in the theory of hydrostatic gravitating structures; Eddington (1926) introduced a related quantity β in his Standard model, $S_\gamma/\Re = 4Y(1-\beta)/\beta$, which appears in the famous quartic equation, $1-\beta = 0.00298\,(m/Y^2)^2\beta^4$, where m is the stellar mass in solar units and Y is the number of pressure-contributing particles per baryon (an ideal gas of matter plus black body radiation is assumed). For most stars of interest to us for nucleosynthesis, $S_\gamma/\Re$ lies in the range of 0.3 to 30, while cosmological values range from 10^8 to 10^{10}. Values for stellar quasistatic burning range about unity, while explosive values are usually around 10, an interestingly restricted range.

The radiation entropy is one parameter that affects the production ratio of carbon to oxygen. These elements, the fourth and third most abundant, are predominantly in the form of the isotopes ^{12}C and ^{16}O, which are made in helium burning. Carbon is made by the triple-alpha reaction, which is proportional to the number of ^{4}He triples (proportional to ρ^3 in a unit volume), while destruction (to form ^{16}O) is proportional to the number of ^{4}He + ^{12}C pairs (proportional to ρ^2). Thus, carbon production beats carbon destruction at higher density. Massive stars have higher $S_\gamma/\Re$, hence lower density for a given burning temperature. Massive stars make almost all of the ^{16}O, while intermediate-mass stars make significant amounts ^{12}C.

A complication to this simple picture of mass dependence is that ^{12}C depletion occurs rapidly as ^{4}He is exhausted, so that incomplete helium burning favors ^{12}C production (this case applies to yields from intermediate-mass stars). Late mixing of new ^{4}He into a helium burning region enhances destruction over ^{12}C production. The theorist may adjust the predicted carbon and oxygen yields by changing the reaction rates, the ratio of massive to intermediate-mass stars, or the nature of the convective mixing process. Plausible choices do give plausible results, but this is still a thorny issue.

1.2.2 The Bulk Yields

The *bulk yield* specifies how much of a given star is processed by each burning stage, for the most abundant elements. The high abundance of carbon (fourth) and oxygen (third) in the solar pattern is due to neutrino cooling; without it these fuels would themselves be consumed by subsequent burning stages. Helium burning, which is cooled by photon diffusion, produces C and O. The next stage, carbon burning, is cooled by neutrino emission; because this process is local and is more vigorous at higher temperature, the stellar structure changes. The carbon burning region tends to be smaller (in mass) so that more C and O survive. Subsequent burning stages (neon, oxygen, silicon) increase the effect.

The burning separates, usually, into the following stages: hydrogen, helium, carbon, neon, oxygen, and silicon burning. Lower-mass stars may not proceed through all these stages if they can loose mass and become a white dwarf. Table 1.1 summarizes the properties of each stage. Together these produce all of the abundant elements except for the H and He from the Big Bang.

The *s*-process, *r*-process, and *p*-process are important diagnostics (Meyer 1994), as they make many rare nuclei but involve less than 10^{-6} of the solar abundance pattern. Only the

Table 1.1. *Bulk Nucleosynthesis Processes*

Process	Reaction	Temperature (K)	Cooling	Products
Hydrogen	pp	2×10^7	photons	He
	CNO	3×10^7	photons	He; N, Na
Helium	$3\alpha \rightarrow^{12}$ C	2×10^8	photons	C
	^{12}C$(\alpha,\gamma)^{16}$O			O
Carbon	^{12}C$+$ ^{12}C	9×10^8	neutrinos	Ne, Na, Mg, Al
Neon	^{20}Ne$(\gamma,\alpha)^{16}$O	1.5×10^9	neutrinos	O, Mg, Al
Oxygen	^{16}O$+$ ^{16}O	2×10^9	neutrinos	Si, S, Ar, Ca
Silicon	^{28}Si(γ,α)	3.5×10^9	neutrinos	Fe,

s-process is thought to be produced in a photon-cooled environment (double shell burning of H and He in intermediate-mass stars, predominantly).

1.2.3 Neutron Excess

The yields of nuclei depend upon the nuclei being produced, but also upon their surviving. Nuclear stability reflects nuclear binding, which exhibits strong systematic properties. These systematics were observed in the Seuss & Urey (1956) abundances by B^{2}FH and Cameron (1957), and still have relevance. Nuclei tend to be more stable if they have equal numbers of neutrons and protons (Z = N), even numbers of neutrons (even N), and even numbers of protons (even Z). However, protons repel by Coulomb forces, so that nuclei with larger Z are more tightly bound if they are neutron rich (this is why supernovae shine: explosive burning of Z = N matter proceeds up to ^{56}Ni, the most bound nucleus with Z = N, and this decays by the weak interaction to ^{56}Fe, sufficiently slowly that it illuminates the expanded gas efficiently).

Below the iron peak, the abundance of odd-Z elements is sensitive to the relative abundance of neutrons and protons in the environment in which they are formed. The most bound isotopes will have even N. For example, ^{23}Na has Z = 11 and N = 12. There is one excess neutron. Similarly, ^{27}Al has Z = 13 and N = 14, with one excess neutron. If there is a paucity of excess neutrons, Na and Al will be rare.

The *neutron excess* is defined as $\eta = \Sigma_i Y_i (N_i - Z_i)$, the fraction of extra neutrons per baryon. Charge neutrality of the plasma relates this to the ratio of electrons to baryons, $Y_e = \Sigma_i Y_i Z_i = (1-\eta)/2$.

The neutron excess is modified in stars by several processes. Ordinary hydrogen burning is equivalent to $4\mathrm{p} + 2\mathrm{e}^- \rightarrow^4 \mathrm{He} + 2\nu$. If we start with pure H and He, then the original proton-rich material changes to $\eta \rightarrow 0$. After hydrogen burning we are interested in small deviations of η above zero.

The most important processes are:

- CNO-produced nitrogen gives $^{14}N(\alpha,\gamma)^{18}F(\beta^{+},\nu)^{18}O$, with and excess of two neutrons per ^{18}O. For solar system initial abundances, $\eta \approx 2 \times 10^{-3}$, which is about right for nucleosynthesis.
- Auxillary reactions during carbon burning are $^{12}C(p,\gamma)^{13}N(\beta^{+},\nu)^{13}C$, and $^{12}C+^{12}C \rightarrow ^{23}Mg+$ n, followed by $^{23}Mg \rightarrow ^{23}Na+e^{+}+\nu$ and related reactions (Arnett & Truran 1967). This gives a neutron excess that is less than, but approaching, $\eta = 2 \times 10^{-3}$.
- Electron captures during hydrostatic oxygen burning and silicon burning (Thielemann & Arnett 1985). This can greatly exceed $\eta = 2 \times 10^{-3}$ and be too large for nucleosynthesis of the solar system abundance pattern. Such matter is presumed to be doomed for incorporation in a neutron star or black hole, and theorists often enforce this result.

The N abundance from hydrogen burning derives from the CNO isotopes initially present in the star, which come from an earlier epoch of nucleosynthesis. This is an example of *seconday* nucleosynthesis (Arnett 1971). The carbon burning example does not depend upon any previous heavy elements ($Z > 2$), and is a *primary* nucleosynthesis process because the ^{12}C was formed by helium burning in the same star.

In this simple picture we would expect the abundance of odd-Z elements below the iron peak to be even more underabundant in metal-poor stars (*secondary*). This effect is mitigated by the *primary* production of neutron excess in carbon burning, which also produces Na and Al. Neon and oxygen burning further damp out the effect, with a resulting trend toward *primary* behavior.

The *r*-process and the *s*-process are dominated by the capture of free neutrons, with the captures being rapid compared to beta decay for the *r*-process and slow for the *s*-process. The source of the neutrons is closely related to the question of neutron excess.

For the *s*-process in intermediate-mass stars, the sources are $^{13}C(\alpha,n)^{16}O$ and marginally $^{22}Ne(\alpha,n)^{25}Mg$ for intermediate-mass stars (Busso, Gallino, & Wasserburg 1999; Busso et al. 2001; Lugaro et al. 2003). The predictions involve parameterized estimates of mixing during the inter-flash phase of the double shell evolution. A weak component of the *s*-process occurs in core helium burning and shell carbon burning in massive stars (Arnett 1996; The, El Eid, & Meyer 2000). Here the results depend upon models of the mixing process used in the stellar model construction.

The site of the *r*-process is still unclear, but is probably related to matter of high neutron excess in a core collapse supernova. Given the ambiguity of these conditions, the details of the process itself are uncertain (Freiburghaus et al. 1999; Meyer 2002). The initial enthusiasm for the neutrino wind model (Woosley & Hoffman 1992) seems to have been premature (Witti, Janke, & Takahashi 1994; Woosley et al. 1994; Freiburghaus et al. 1999). To circumvent these difficulties, Qian & Wasserburg (2003) have used a phenomenological approach. With 8-meter class telescopes, direct observations, such as those by Johnson (2002) and Johnson & Bolte (2002), are beginning to provide significant constraints.

1.2.4 Time Scales

Nucleosynthesis in stars may be divided into two qualitatively different categories: *quasistatic* or *explosive* burning. The *r*-process, with its time scale estimated from the needed beta decay rates to be of order of seconds (B^2FH; Cameron 1957), was seen early to be an explosive process, and the *s*-process to be quasistatic. Internal evidence in the isotopic abundances above iron suggest that carbon and neon burning were quasistatic (Arnett 1996, § 9.6; see also The et al. 2000). Oxygen burning, on the other hand, produces too large a neutron excess during quasistatic burning to match the solar system isotopic pattern, and is likely to be an explosive process for the matter that contributes to the yield.

1.3 Problems

There are several open questions that reduce the reliability of predictions of stellar yields.

1.3.1 Initial Mass Function

Any prediction of stellar nucleosynthesis must involve the question of how many stars, and of what kind, compose a stellar generation? The initial distribution of stars in mass, for a given generation of star formation, is called the initial mass function. Figure 1.1 illustrates the problem in a beautiful way; it is a galaxy in starburst mode. The clumps of massive new stars are eye-catching, but emphasize that massive stars are not uniformly distributed in space. Further, this galaxy is in an active time for star formation, so that there may be a nonuniform distribution in time as well.

Figure 1.2 illustrates the problem quantitatively. The logarithm of the return mass f, in solar units, is plotted versus the stellar mass, for an idealized cluster having $10^4\ M_\odot$ total mass in stars of stellar mass $m > 1\,M_\odot$. The initial mass function has a Salpeter slope. The binning is logarithmic in stellar mass (horizontal axis); the error bars represent Gaussian fluctuation due to a finite number of stars in each bin. Some interesting mass values are indicated on the horizontal axis: the mass at which the helium flash occurs (He flash), $M_{\rm up}$ is the mass above which nondegenerate carbon ignition follows helium exhaustion directly, O+O is the mass above which oxygen burning occurs, SN 1987A denotes the putative mass of that supernova progenitor, and WR denotes a typical mass of a Wolf-Rayet star.

Modern estimates of the mass of white dwarfs from intermediate-mass stars imply that of order half of the mass in stars above $1\,M_\odot$ is returned to the interstellar medium. This is considerably larger than old estimates, and dilutes the yield of heavy elements from more massive stars (and modifies old arguments: Arnett 1978; Wheeler, Miller, & Scalo 1980; see also Chiosi 1979; Maeder 1981). The limitations on the brown dwarf mass function (Chabrier 2002) further reduce the amount of matter removed per generation from the stellar birth-death cycle.

For stars above $10M_\odot$ the fluctuations in stellar number become an increasing worry. This idealized cluster is more massive than usual for a typical open cluster, but is consistent with what Slesnick, Hillenbrand, & Massey (2002) find for h and χ Persei (compare their Fig. 8 with Fig. 1.2).

If we take $M_{\rm up}$ as the boundary between intermediate-mass and massive stars, we see that the dominant mass return is from the intermediate-mass stars. Relatively modest nucleosynthesis in this mass range may have significant consequences, even beyond the ususal discussion of the *s*-process.

1.3.2 Nonexplosive Mass Loss

The radiation-driven wind theory of mass loss from OB stars now gives a reliable and understandable basis for stellar evolution with mass loss for massive stars in this part of the Hertzsprung-Russell diagram (Kudridzki & Puls 2000; Paldrach, Hoffman, & Lennon

Fig. 1.1. A galaxy (NGC 3310) in starburst mode, indicating the inhomegeity of massive stars in both time and space (Hubble Heritage, NASA, STScI).

2001; Kudridzki 2002). The situation for cool stars is less settled (Wallerstein & Knapp 1998; Willson 2000). ISOCAM observations of massive Galactic globular clusters suggest that significant mass loss occurs only at the very end of the red giant branch, is episodic, and does not show a crucial dependence upon cluster metallicity (Origlia et al. 2002). These stars are of low mass, but do contribute to the mass budget for matter returned to the interstellar medium, and may give clues for the mechanism for mass loss by more massive cool stars. For the mass range $1 \leq m/M_{\odot} \leq 10$, Willson (2000) suggests that empirical relationships between mass loss rates and stellar parameters, so beloved by stellar theorists, are determined mostly by selection effects, and that mass loss rates increase precipitously

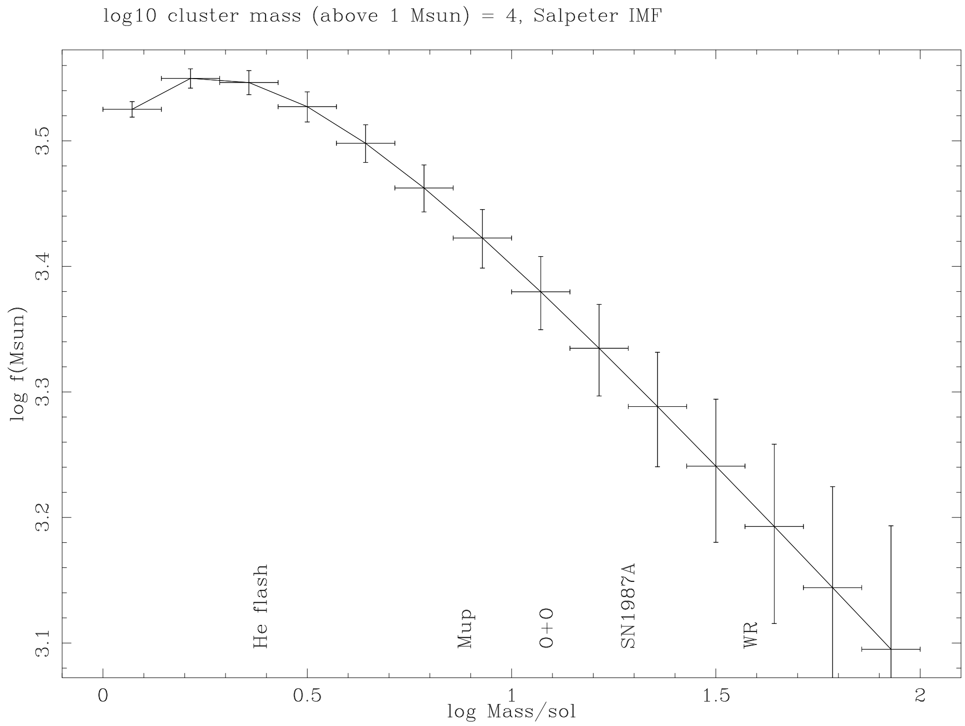

Fig. 1.2. The massive and the intermediate-mass stars dominate the return of matter to the interstellar medium. The amount of returned matter is significantly higher with modern estimates of the mass of the white dwarf remnant and the brown dwarf mass function.

as stars become brighter, larger, and cooler. Unfortunately, these are the stars that ascend the asymptotic giant branch and are thought to produce most of the *s*-process, and the mass loss affects the predictions of yields (Frost & Lattanzio 1996; Charbonnel 2002; Lattanzio 2002). There are a variety of unexplored aspects of the physics of such mass loss (e.g., Van Horn et al. 2003). The situation for massive cool stars is more obscure, both figuratively and literally; they tend to be shrouded in dust formed in ejected material. Their evolutionary status is a subject of debate (Langer et al. 1994; Crowther, Hiller, & Smith 1995a, b, c; Crowther et al. 1995), and the detailed mechanism of their mass loss seems unclear.

1.3.3 Rotation

While rotation has been an issue for star formation theory for centuries, it is also an issue for stellar death, as Figure 1.3 vividly shows. What happens between these extremes?

Most discussions of rotation and stellar evolution follow the approach of Endal & Sofia (1976), in which the Lagrangian shells of a stellar model are presumed to be rotationally deformed from spheres into oblate figures. Because only one dimension is computed, state variables must be uniform along these shells. This approximation can only be valid if there is some physical mechanism that insures it. If mixing along horizontal directions is fast, as would be the case if g-modes are a dominant mechanism for mixing (Talon & Zahn 1997; Maeder & Zahn 1998), this could be valid. The implication is that the evolutionary

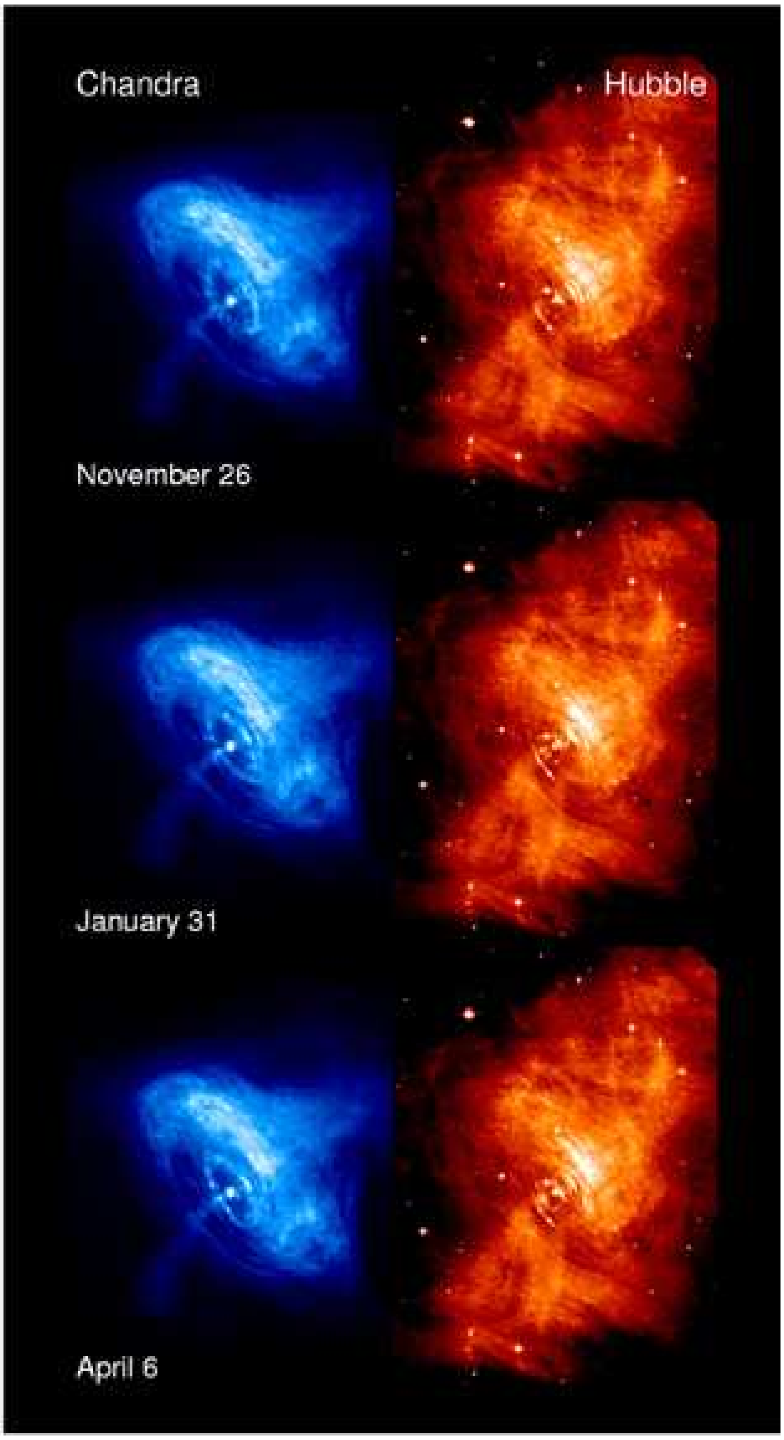

Fig. 1.3. The Crab nebula shows dramatic evidence of rotation in its collapsed core. The images are in X-rays (*Chandra*) and visible light (*HST*) (NASA/CXC/ASUIJ, Hester et al. 2002; NASA/HST/ASUIJ, Hester et al. 2002).

time scale is long compared to the horizontal mixing time scale. Maeder and Meynet have explored stellar evolution with rotation from this perspective in a extensive series of papers (Maeder 1997, 1999; Meynet & Maeder 1997, 2000, 2001, 2002; Maeder & Meynet 2000a, b, 2001), which set the standard for this topic. Heger, Woosley, & Langer (2000) have run a grid of models of rotating and nonrotating massive stars of solar metallicity from pre-main sequence to core collapse. Langer et al. (1999) have extended this to intermediate-mass stars.

Even with the most optimism that can be gathered, it appears that such a one-dimensional approximation breaks down badly for the oxygen burning state (Arnett 1994; Bazán & Arnett 1998), because the mixing time scale and the evolutionary time scale are becoming similar. Whatever the outcome, it is clear that we must explore the nonspherical models of late stellar evolution before we understand these stages. They are crucial for yields as they involve major shell burning stages (carbon, neon, and oxygen), which provide much of the pre-explosion nucleosynthesis. The oxygen shell provides most of the explosive burning, including the formation of ^{56}Ni. The lack of symmetry of these stages will be imprinted upon the core collapse, and may affect the explosion mechanism.

1.3.4 Binarity

Perhaps half of the massive stars have companions (i.e. are in binaries). The nature of their joint evolution is affected by mass loss, which, as we have seen, is a problem for the cooler side of the Hertzsprung-Russell diagram. Angular momentum loss affects the orbital properties of the binary, complicating the picture. Mass stripping, tidal interactions, and merger are fundamentally three-dimensional phenomena, and to make things more difficult, may also involve detailed radiative transfer (not just diffusion) and magnetohydrodynamics. It is widely stated that Type Ia supernova are produced in binary systems, but quantitative treatment of the evolution to explosion, in a realistically multidimensional way, is only beginning (e.g., Piersanti et al. 2003).

1.3.5 Mix

Figure 1.4 shows the inhomogeneity in the products of explosive nucleosynthesis in the supernova remnant Cassiopea A. Silicon is produced by explosive or quasistatic oxygen burning. Calcium is produced by explosive oxygen burning, most likely. Iron can be produced by oxygen burning that continues into silicon burning. All have different shapes in the image. This could be due to different degrees of explosive burning, with large burning making Ca, little burning leaving the Si from quasistatic burning intact, and extreme burning making Fe. It could also be due to inhomogeneity in the progenitor.

Optical data (Fesen 2001), infrared data (Douvion, Lagage, & Cesarsky 1999) from ISO-CAM, X-ray data (Hughes et al. 2000) from *Chandra* and (Willingale et al. 2003) from *XMM-Newton*, and gamma-ray lines (Vink et al. 2001) are giving a much improved picture of Cass A. In addition to Si, Ca, and Fe, the optical data include O and Ar (incomplete oxygen burning) and N and H (pre-explosion mass loss?). The infrared data include a silicate layer, a S and Ar layer, and a Ne layer. The gamma-lines give ^{44}Ti. All show evidence for inhomogeneity in composition and kinematics. The best choice for the progenitor seems to be fairly massive, possibly a 10 to 30 solar mass Wolf-Rayet star, but details of the identification are sketchy.

Although there is some success in identifying isotopic anomalies in pre-solar grains with

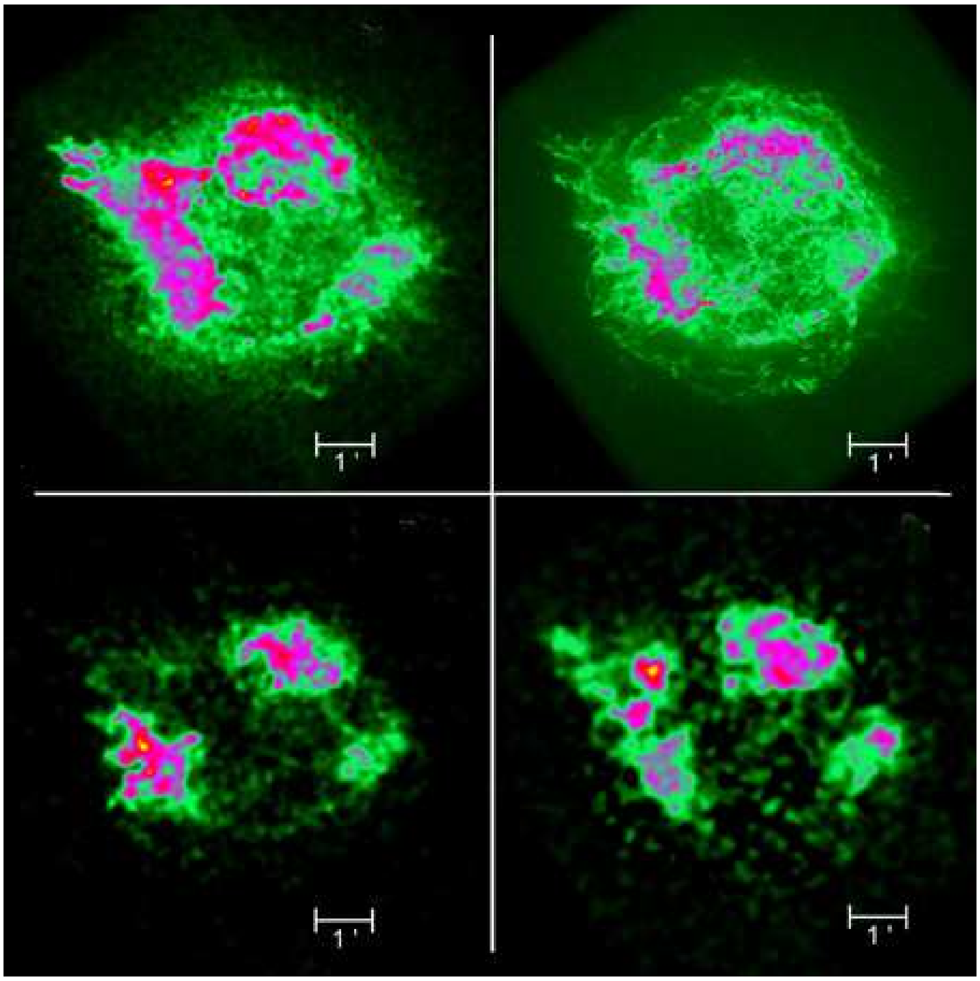

Fig. 1.4. This *Chandra* X-ray image of Cassiopea A shows inhomogeneity in the products of explosive nucleosynthesis (NASA/GSFC, Hwang et al. 2001). The upper left image is broadband, and in clockwise order are images of emission from silicon, iron, and calcium.

asymptotic giant branch stars (Choi, Wasserburg, & Huss 1999), there are problems with grains exhibiting supernova nucleosynthesis. Although aspects of explosive processes, such as extinct ^{44}Ti and ^{28}Si excesses, are found, extreme mixing models are required to match the supernova predictions (Zinner 1998). Perhaps this difficulty is related to the enforced spherical symmetry in the supernova models.

If highly evolved stars no longer maintain the symmetry of spherical shells, what will be the consequences for nucleosynthesis yields? Suppose the star to be made not of spherical shells, but of a patchwork of blobs. Neutrino cooling would lower the entropy of a blob, causing it to sink, moving past its neighbors. This would continue until the temperature rose enough to ignite a fuel. This would increase the entropy, making the blob buoyant, and causing it to rise. We might imagine a cycle of repeated rising and falling, with some fuel consumed each time. The temperature at which falling was reversed would depend upon the composition of the blob, so that on average there *would* be a layering according to composition, but it would be broken by fluctuations. Some burning flashes would be more vigorous, giving larger excursions, spreading ashes in ways not seen in one-dimensional simulations. Could a few vigorous oxygen flashes make ^{56}Ni and carry it out far enough to explain the early appearance of ^{56}Co gamma-ray lines in SN 1987A? What would be the effect of a supernova shock on the inhomogeneous oxygen-rich layer? Are nuclear-energized pulsations driven by the accelerating contraction of the core during silicon burning? How does rotation couple to the burning, and does this qualitatively change the nature of the inital core collapse model? The range of possiblities is larger than yet considered.

1.3.6 Progenitors

Mathematically, explosions are exponentiating solutions, which are sensitive to initial conditions. Given that we have no agreed-upon mechanisms for either thermonuclear or core collapse supernovae, it would be good to know what the progenitors are. For SN 1987A we know the progenitor had a helium core of about $6M_\odot$ from the luminosity of the B3 star, but beyond that disagreement sets in (the main sequence mass for a single star would have been $20M_\odot$). For SN 1993J, Smart et al. (2002) suggest a similar luminosity, implying a similar mass, but a K0 spectral type. These authors estimate the mass of the progenitor of SNe II-P 1999em to be $12\,^{+1}_{-1}M_\odot$. Smartt et al. (2001) estimated the mass of the progenitor of SN 1999gi to be $9\,^{+3}_{-2}M_\odot$. For SN II-P 2001du, Smartt et al. (2003) estimate the mass to be less than $15M_\odot$, and with new data, revise that of SN 1999gi to $12M_\odot$, and that of SN 1998em to less than $15M_\odot$.

From a different perspective, Hamuy (2003) has used photometry and spectroscopy of 24 SNe II-P to derive properties of their explosions and their progenitors. The nickel masses range from 0.00166 to $0.26M_\odot$. The explosion energies ranged between 0.6 to 5.5×10^{51} erg, ejected masses from 14 to $56M_\odot$, and radii from 80 to $600R_\odot$. He infers a continuous distribution of energies below 8×10^{51} erg.

Howell (2001) finds that subluminous SNe Ia come from an old population. The fact that subluminous SNe Ia and overluminous SNe Ia come from different progenitor populations is a prediction of the white dwarf merger scenario (Iben & Tutukov 1984).

While still incomplete, these new data provide interesting challenges: can we connect observed supernovae to stellar evolutionary sequences?

1.3.7 Ejection and Explosion Mechanisms

The question of explosion mechanisms is still open. Core collapse clearly happened in SN 1987A, but the theoretical understanding is still incomplete.

Travaglio, Kifonidis, & Müller (2004) discuss the nucleosynthesis in core collapse supernovae, as seen in 1-D and 2-D hydrodynamic simulations; see Kifonidis et al. (2003) for a discussion of the hydrodynamic behavior. A satisfactory explanation for the early escape of gamma-lines from ^{56}Co from SN 1987A still eludes us. These simulations basically assume an explosion from core collapse and examine its consequences.

The problem of that explosion is unsolved (see, e.g., Janka 2001; Liebendörfer et al. 2001; Rampp et al. 2002; Buras et al. 2003). Fully 3-D simulations of the core collapse are beginning to appear (Fryer & Warren 2002), which may clarify the effect of 2-D versus 3-D.

For thermonuclear explosions the question remains: detonation or deflagration? One

Table 1.2. *Stellar Evolution with Detailed Yields*

Reference	Masses/$M_\odot$	Metallicity	Networks	Comment
WZW78	15, 25	solar	19 NSE(121)	pre-MS to collapse
WW95	11–40	Z = 0,10^{-4},0.01, 0.1,1	19 200	pre-MS to collapse
R02	15, 19, 20, 21, 25	solar	19 700–2200	NON-SMOKER rates
HW02	65–130, steps of $\Delta M = 5$	solar	19 304,477(exp)	He cores
TNH96	13, 15, 20, 25	solar	299	
I99	1.45	solar	299	SNe Ia
MM	0.8–120	Z = 0.001 to 0.08	19	mass loss rotation
CLS98	25	solar	149	pre-MS to collapse
LSC00	13–25	solar	149	pre-MS to collapse
CL02	15, 20, 25, 35, 50, 80	Z = 0	179	pre-MS to collapse
LC98	13–35	solar	267	pre-MS to collapse
TEM00	15, 20, 25, 30	solar	659	Ne ignition
APB96	20	solar	96	Ne-exhaustion Göttigen code

References: WZW78, Weaver, Zimmermann, & Woosley (1978); WW95, Woosley & Weaver (1995); R02, Rauscher et al. (2002); HW02, Heger & Woosley (2002); TNH96, Thielemann, Nomoto, & Hashimoto (1996); I99, Iwamoto et al. (1999); MM, Maeder & Meynet (1997-2003); CLS98, Chieffi, Limongi, & Straniero (1998); LSC00, Limongi, Straniero, & Chieffi (2000); CL02, Chieffi & Limongi (2002); LC98, Limongi & Chieffi (1998); TEM00, The, El Eid, & Meyer (2000); APB96, Aubert, Prantzos, & Baraffe (1996).

of the most interesting developments are the large-scale 3-D simulations of Gamezo et al. (2003). They numerically simulate the deflagration stage of a thermonuclear supernova (SN Ia), and find that while the turbulent flame does provide a healthy explosion, it is subject to gravity-induced Rayleigh-Taylor instabilities, and leaves large amounts of unburnt and partially burnt material, whereas observations imply that such material only exists in the outer (high-velocity) layers. They suggest that a transition of deflagration to detonation may be the solution.

1.4 Progress

The current state-of-the-art for supernova nucleosynthesis simulations is illustrated by the work of several groups, in which extensive networks have been coupled to the stellar evolutionary equations. Several are summarized below in Table 1.2; the list is quite incomplete, but fairly representative. Woosley, Heger, & Weaver (2002) have recently produced an extensive review. In addition, the intermediate-mass stars make an important contribution (see above).

1.5 Conclusions

The numerical simulations of stellar evolution and nucleosynthesis in supernova explosions and double shell burning now produce predictions relevant to observation and experiment. There are still significant disagreements between groups about detail. While we are making progress, we still have a lot of work to do to place these predictions upon a reliable basis, as the discussion above suggests.

References

Arnett, D. 1968, in Stellar Evolution, ed. R. Stein & A. G. W. Cameron (New York: Plenum Press)
——. 1971, ApJ, 166, 153
——. 1978, ApJ, 219, 1008
——. 1994, ApJ, 427, 932
——. 1996, Supernovae and Nucleosynthesis (Princeton: Princeton Univ. Press)
Arnett, D., & Truran, J. W. 1967, ApJ, 157, 339
Aubert, O., Prantzos, N., & Baraffe, I. 1996, A&AS, 312, 845
Bazán, G., & Arnett, D. 1998, ApJ, 496, 316
Buras, R., Rampp, M., Janka, H.-Th., & Kifonidis, K. 2003, Phys. Rev. Lett., 90, 1101
Burbidge, E. M., Burbidge, G., Fowler, W. A., & Hoyle, F. 1957, Rev. Mod. Phys., 29, 547
Busso, M., Gallino, R., Lambert, D., Travaglio, C., & Smith, V. 2001, ApJ, 557, 802
Busso, M., Gallino, R., & Wasserburg, G. J. 1999, ARA&A, 37, 239
Cameron, A. G. W. 1957, Chalk River Report CRL-41
Charbonnel, C. 2002, Ap&SS, 281, 161
Charbrier, G. 2002, ApJ, 567, 304
Chieffi, A., & Limongi, M. 2002, ApJ, 577, 281
Chieffi, A., Limongi, M., & Straniero, O. 1998, ApJ, 502, 737
Chiosi, C. 1979, A&AS, 80, 252
Choi, B.-G., Wasserburg, G. J., & Huss, G. R. 1999, ApJ, 522, L133
Crowther, P. A., Hillier, D. J., & Smith, L. J. 1995a, A&AS, 293, 172
——. 1995b, A&AS, 293, 403
——. 1995c, A&AS, 302, 457
Crowther, P. A., Smith, L. J., Hillier, D. J., & Schmutz, W. 1995, A&AS, 293, 427
Douvion, T., Lagange, P. O., & Cesarsky, C. J. 1999, A&AS, 532, L111
Eddington, A. S. 1926, The Internal Constitution of the Stars (New York: Dover), reprinted 1959
Endal, A. S., & Sofia, S. 1976, ApJ, 210, 184
Fesen, R. A. 2001, ApJS, 133, 161
Freiburghaus, C., Rembges, J.-F., Rauscher, T., Kolbe, E., Thielemann, F. K., Kratz, K.-L., Preiffer, B., & Cowan, J. J. 1999, ApJ, 516, 381
Frost, C. A., & Lattanzio, J. C. 1996, ApJ, 473, 383
Fryer, C., & Warren, M. 2002, ApJ, 574, L65
Gamezo, V. N., Khokhlov, A. M., Oran, E. S., Chtchelkanova, A. Y., & Rosenberg, R. O. 2003, Science, 299, 77
Hamuy, M. 2003, ApJ, 582, 905
Heger, A., & Woosley, S. E. 2002, ApJ, 567, 532
Heger, A., Woosley, S. E., & Langer, N. 2000, NewAR, 44, 297
Hester, J., et al. 2002, ApJ, 577, L49
Howell, D. A. 2001, ApJ, 554, L193
Hughes, J. P., Rakowski, C. E., Burrows, D. N., & Slane, P. O. 2000, ApJ, 528, 109
Hwang, U., Szymkowiak, A. E., Petre, R., & Holt, S. S. 2001, ApJ, 560, L175
Iben, I., Jr., & Tutukov, A. V. 1984, ApJS, 54, 335

Iwamoto, K., Brachwitz, F., Nomoto, K., Kishimoto, N., Umeda, H., Hix, W. R., & Thielemann, F.-K. 1999, ApJS, 125, 439
Janka, H.-Th. 2001, A&AS, 368, 527
Johnson, J. A. 2002, ApJS, 139, 219
Johnson, J. A., & Bolte, M. 2002, ApJ, 579, 616
Kifonidis, K., Plewa, T., Janka, H.-Th., & Müller, E. 2003, A&AS, 408, 621
Kolb, E. W., & Turner, M. S. 1990, The Early Universe (Redwood City, California: Addison-Wesley)
Kudritzki, R. P. 2002, ApJ, 577, 389
Kudritzki, R. P., & Puls, J. 2000, ARA&A, 38, 613
Langer, N., Hamann, W.-R., Lennon, M., Najarro, F., Pauldrach, A. W. A., & Puls, J. 1994, A&AS, 290, 819
Langer, N., Heger, A., Wellstein, S., & Herwig, F. 1999, A&AS, 346, L37
Lattanzio, J. C. 2002, NewAR, 46, 469
Liebendörfer, M., Mezzacappa, A., Thielemann, F.-K., Messer, O. E. B., Hix, W. R., & Bruenn, S. W, 2001, Phys. Rev. D, 63, 103004
Limongi, M., & Chieffi, A. 2003, ApJ, 592, 404
Limongi, M., Straniero, O., & Chieffi, A. 2000, ApJS, 129, 625
Lugaro, M., Herwig, F., Lattanzio, J., Gallino, R., & Straniero, O. 2003, ApJ, 586, 1305
Maeder, A. 1981, A&AS, 101, 385
——. 1997, A&AS, 321, 134
——. 1999, A&AS, 347, 185
Maeder, A., & Meynet, G. 2000a, A&AS, 361, 101
——. 2000b, A&AS, 361, 159
——. 2001, A&AS, 373, 555
Maeder, A., & Zahn, J. P. 1998, A&AS, 334, 1000
Meyer, B. 1994, ARA&A, 32, 153
——. 2002, Phys. Rev. Lett., 89, 1101
Meynet, G., & Maeder, A. 1997, A&AS, 321, 465
——. 2000, ARA&A, 38, 143
——. 2001, A&A, 373, 555
——. 2002, A&AS, 390, 561
Origlia, L., Ferraro, F. R., Fusi Pecci, F, & Rood, R. T. 2002, ApJ, 571, 458
Paldrach, A. W. A., Hoffman, T. L., & Lennon, M. 2001, A&AS, 375, 161
Piersanti, L., Gagliardi, S., Iben, I., Jr., & Tornambé, A. 2003, ApJ, 583, 885
Qian, Y.-Z., & Wasserburg, G. J. 2003, ApJ, 588, 1099
Rampp, M., Buras, R., Janka, H.-Th., & Raffelt, G. 2002. in Proc. 11th Workshop on Nuclear Astrophysics, ed. W. Hillebrandt & E. Müller (Garching: Max-Planck-Institut für Astrophysik), 119
Rauscher, T., Heger, A., Hoffman, R. D., & Woosley, S. E. 2002, ApJ, 576, 323
Seuss, H. E., & Urey, H. C. 1956, Rev. Mod. Phys., 28, 53
Slesnick, C. L., Hillenbrand, L. A., & Massey, P. 2002, ApJ, 576, 880
Smartt, S. J., Gilmore, G. E., Tout, C. A., & Hodgkin, S. T. 2002, ApJ, 565, 1087
Smartt, S. J., Gilmore, G. E., Trentham, N., Tout, C. A., & Frayn, C. M. 2001, ApJ, 556, L29
Smartt, S. J., Maund, J. R., Gilmore, G. E., Tout, C. A., Kilkenny, D., & Benetti, S. 2003, MNRAS, 343, 735
Talon, S., & Zahn, J. P. 1997, A&AS, 317, 479
The, L.-S., El Eid, M., & Meyer, B. S. 2000, ApJ, 533, 998
Thielemann, F.-K., & Arnett, D. 1985, ApJ, 295,604
Thielemann, F.-K., Nomoto, K., & Hashimoto, M. 1996, ApJ, 460, 408
Travaglio, C., Kifonidis, K., & Müller, E. 2004, in Carnegie Observatories Astrophysics Series, Vol. 4: Origin and Evolution of the Elements, ed. A. McWilliam & M. Rauch (Pasadena: Carnegie Observatories, http://www.ociw.edu/symposia/series/symposium4/proceedings.html)
Van Horn, H., Thomas, J. H., Frank, A., & Blackman, E. G. 2003, ApJ, 585, 983
Vink, F., Laming, J. M., Kaastra, J. S., Bleeker, J. A. M., Bloemen, H., & Oberlack, U. 2001, ApJ, 560, L79
Wallerstein, G., & Knapp, G. R. 1998, ARA&A, 36, 369
Weaver, T. A., Zimmermann, G. B., & Woosley, S. E. 1978, ApJ, 225, 1021
Wheeler, J. C., Miller, G. E., & Scalo, J. M. 1980, A&AS, 82, 152
Willingale, R., Bleeker, J. A. M., van der Heyden, K. J., & Kaastra, J. S. 2003, A&AS, 398, 1021
Willson, L. A. 2000, ARA&A, 38, 573
Witti, J., Janka, H.-Th., & Kakahashi, K., 1994, A&AS, 286, 841

Woosley, S. E., Heger, A., & Weaver, T. A. 2002, Rev. Mod. Phys., 74, 1015
Woosley, S. E., & Hoffman, R. D. 1992, ApJ, 395, 202
Woosley, S. E., & Weaver, T. A. 1995, ApJS, 101, 181
Woosley, S. E., Wilson, J. R., Mathews, G. J., Hoffman, R. D., & Meyer, B. S. 1994, ApJ, 433, 229
Zinner, E. 1998, Ann. Rev. Earth Planet. Sci., 26, 147