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# Nucleosynthesis in Stars: Recent Developments

David Arnett and Grant Bazan

The development of new observational, experimental, and computational technologies is changing our understanding of the origins of the elements by thermonuclear burning in stars. Gamma-ray lines from newly made radioactive nuclei have been identified using instruments onboard low-Earth orbiting satellites. Grains in meteorites have isotopic anomalies which suggest that the grains were put together in a stellar explosion such as a supernova. Computer simulations allow such anomalies to be used to probe how these events happen. The simulations are being independently tested by experiments with high-energy density lasers. These developments are beginning to provide a quantitative diagnostic of galactic evolution, and of the epoch of formation of the first stars and galaxies.

Four decades ago the seminal idea that essentially all of the elements were made by thermonuclear burning in stars (stellar nucleosynthesis) was codified (*1*, *2*). Later, astronomical observations (*3*, *4*) suggested (*3*) that the elements were formed by some other process early in cosmological history, perhaps in the Big Bang itself. Ironically, existing analyses on Xe (*5*) and Ne (*6*) in meteorites suggested that the elements were formed by ongoing stellar nucleosynthesis, but this data was not considered by (*3*) and (*4*). The notion of ongoing stellar nucleosynthesis was difficult to prove. To understand the context, consider this sketch of the history of matter (*7*). First, the Big Bang produces a bland distribution of nuclei: H, D, $^3$He, $^4$He, and traces of Li, Be, and B isotopes. This is followed by a poorly understood epoch in which the first stars and galaxies form. Massive stars burn quickly and brightly and become unstable. The most massive stars explode as supernovae (SNe), ejecting newly synthesized elements from C to U; less massive stars enrich the surrounding gas less dramatically. The ejected elements are incorporated into new generations of stars, and eventually into planets and other objects.

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Today the nature of the debate is different because advances in astronomical instruments has improved and extended the observational field of view. Charge-coupled devices (CCDs), with higher sensitivity and linearity, have replaced photographic plates. Telescopes in orbit, which surmount the pernicious veil of atmosphere, show wavelengths not visible from the ground. We now can observe essentially the whole electromagnetic spectrum, from gamma rays to radio waves.

For most of their lives, stars are spherical to a good first approximation. The star is divided into many (hundreds to thousands) spherical shells and in this "onion skin" model, each shell is assumed to be chemically homogeneous, with heterogeneity allowed only between shells. Many problems have been solved using this model (*7*). One reason the spherical approximation works is because stars usually evolve slowly, and eventually settle down to this symmetrical form. But as stars become unstable late in their life, this is no longer true. Unstable stars are complex, asymmetric, rapidly varying objects. This is the epoch at which stars eject their nucleosynthesis products. The need to compute not only the evolutionary changes in the spherical shells, but also for "cells" in longitude and latitude within these shells, presents a computational challenge. Fortunately, the new generation of massively parallel computers is powerful enough to allow such demanding simulations, and thus provide an opportunity to match theory against observation and experiment in a quantitative way.

## Recent Nucleosynthesis Observed

Gamma ray lines are electromagnetic radiation of discrete frequencies, produced by nuclear transitions. They are the nuclear analogs of spectral lines produced by transitions in the electron cloud around atoms. Most radioactive nuclei decay with emission of gamma rays and these energies are characteristic of the type of nucleus. Gamma ray lines are deeply attenuated by the atmosphere of Earth, so that astronomical observations of gamma rays must be carried out by orbiting satellites. The existence of radioactive nuclei in significant abundance in space implies production over a time comparable to the decay time of the nuclei. $^{26}$Al has a half-life of about $7 \times 10^5$ years, which is about $5 \times 10^{-5}$ times the age of the Galaxy. The COMPTEL instrument on the Compton Gamma Ray Observatory satellite (CGRO) detected the 1.809-MeV line from the decay of $^{26}$Al in interstellar gas (Fig. 1). This observation ended the contention (*3*) that nucleosynthesis was not a significant ongoing process. Stars are gravitationally bound thermonuclear reactors. In particular, the distribution on the sky of the intensity of the 1.809 MeV gamma ray (Fig. 1) is similar to the distribution of massive stars ($M > 10\ M_\odot$); even the clumping of the gamma ray intensity is simlar to the clumping of massive stars. Massive stars can produce $^{26}$Al in high temperature hydrogen burning, after which it must be advected to the surface, and ejected into space by the mass loss process commonly observed in such objects (*8, 9*).

The brightness of SNe has long been thought to be partly a consequence of the another radioactive decay (*10*), that of newly made $^{56}$Ni to $^{56}$Co and thence to $^{56}$Fe, which is the most abundant isotope of Fe in the solar system and presumably elsewhere. The first detection of gamma line radiation from beyond the solar system was of $^{56}$Co decay in supernova 1987A in the Large Magellanic Cloud (*11–16*). This detection is a direct measure of the synthesis of Fe, the sixth most abundant element (after H, He, O, C, and Ne, which are not made first as radioactive progenitors). Subsequently, lines of the $^{57}$Co, from the chain reaction $^{57}\mathrm{Ni} \rightarrow {}^{57}\mathrm{Co} \rightarrow {}^{57}\mathrm{Fe}$, were found in SN1987A as well. Lines of $^{44}$Ti have been reported (*17*) from the supernova remnant Cas A. See the recent reviews (*18, 19*) for more detail on this active and still unfolding topic.

## The Producers of Nucleosynthesis

Newly formed elements are produced primarily in supernova explosions. There are two varieties of SNe: core collapse, which form neutron stars (pulsars) or black holes, and thermonuclear, which entirely disrupt. Core collapse SNe are identified with two observational classifications: Type II SNe (*20*) and Type Ib and Ic SNe. Supernova 1987A was the best observed core collapse supernova; its progenitor (20 $M_\odot$) was not unlike Rigel, the bright blue star in Orion. Most SNe of Type II will explode when they have swollen to a large size. More massive stars drive off their outer H-rich layers even before they explode; their brightness as SNe is almost entirely due to the radioactive Ni they eject when they explode. The thermonuclear SNe are thought to be what observers call Type Ia SNe (*21*), and are the result of catastrophic thermonuclear burning of C and O in a white dwarf. A nova burns H in a milder way, ejecting only the outer layers of a white dwarf; these too are potential contributors to nucleosynthesis. Less dramatic but still important sources of nucleosynthesis are "intermediate mass" stars (roughly $2 < M/M_\odot < 10$). They provide significant amounts of C and of elements beyond Fe associated with the *s*-process (*22*).

Because SNe are the primary engines of synthesis for atomic nuclei, they are central to any discussion of nucleosynthesis. The two varieties do not produce elements in the same ratios: thermonuclear SNe produce a lot of Ni (which decays to Fe), while core collapse SNe produce a lot of the elements C through Ca, with O the most abundant element (*7, 23, 24*). Simulations (*25–27*) provide predictions of the thermonuclear yields from the layers of ejecta. The excess of neutrons in the matter which just escapes the neutron star (or black hole) provides a promising site for the *r*-process (*22*), which makes some of the trans-iron elements by rapid neutron capture, up to Th and U.

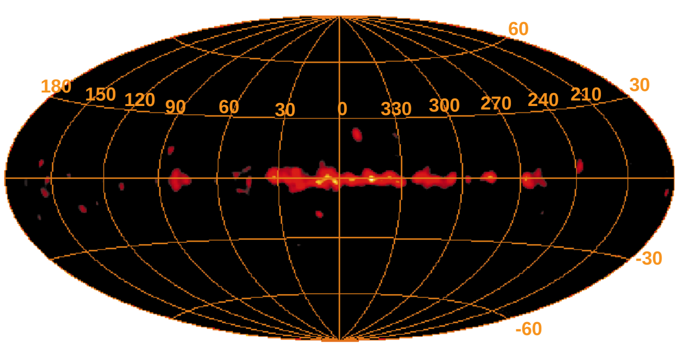

**Fig. 1.** The Milky Way as seen in the 1.809 MeV line from $^{26}$Al decay (*76*), courtesy of R. Diehl. Most of the emission comes from the disk of the Milky Way, where the massive stars are found.

## Stellar Hydrodynamics

Thermonuclear burning changes the composition of the hottest regions of stars. Diffusion of nuclei in the stellar plasma is too slow to remove such gradients, unless accompanied by vigorous mixing. Burning often drives convection, which causes mixing. Stellar evolution theory uses a mixing length model of convection (*28*). Generally, no other mass motion is assumed, although rotation might be important (*28*). Mixing of material occurs only when driven by thermal instability, and is accompanied by the mixing of heat. No mixing occurs beyond the formal boundary of the unstable region. Convection could be approximately spherically symmetric, if the mixing length is small compared to other stellar dimensions, which is not the case. Convective plumes, such as thunderheads, are not spheres. The convective mixing might be roughly spherical if the net effect of many complex motions averages out to a diffusion-like process (the usual approximation). Certainly for rapid evolution as in a presupernova, or a supernova explosion itself, these conditions do not hold, and the spherical approximation fails.

Supernova 1987A showed this in a variety of ways (*29*). Early analysis of the optical spectra (*30*) showed deviations from expectations of spherical hydrodynamic calculations. The "Bochum event" (*31*), a major change in the spectral features, suggested that radioactive Ni had penetrated overlying layers. After 2 weeks, the evolution of luminosity with time required extensive "mixing" of the ejecta, as did the earlier than expected detection of x-rays and gamma rays, also attributed to mixing (*32*). To this is included the shape of the OI emission (*33*) and the differential behavior of neutral to ion lines after day 530 (*34*), which is evidence that some of the ejecta were distributed in discrete clumps.

Simulations of the hydrodynamic instabilities during the explosion (*35*) suggested the possibility that the evolution of the O burning shell should be simulated hydrodynamically up to the onset of instability. This stage was simulated in two dimensions (*36*) and the results are different (Fig. 2) from those using the spherical approximation (*37*). In the hour or so available before core collapse, the O burning shell convects down unburned fuel from above, in unmixed blobs. These blobs of $^{20}$Ne and $^{12}$C burn violently, exceeding the energy release from O burning. The burning is localized in "hot spots", and is episodic. Contrary to mixing length assumptions, some material moves across the formal boundaries for convective instability, allowing stirring over a more extended region. Fuel and ashes are mixed in a clumpy, heterogeneous way. None of these features were seen in the spherically symmetric simulations, and as we shall see below, they may be important. These two-dimensional calculations do simulate convection as a hydrodynamic process, unlike the one-dimensional calculations which use a phenomenological model.

Some aspects of these simulations can be directly tested. The Nova laser (*38*) has been used to generate controlled conditions which hydrodynamically scale to those found in SNe (*39*). The first results of the experiment show good agreement between (i) simulations using the astrophysical methods, (ii) standard hydrodynamic methods (the CALE code) used in the Inertial Confinement Fusion (ICF) community, and (iii) the experiment (*39*).

## Almost Pristine Environments

The Big Bang produces few kinds of elements, only H and He in bulk. These provide only one (H) of the those which are the basic components for life; terrestrial planets could not be constructed from such matter. This adds motivation to a search for environments which show only the first effects of pollution by noncosmological nucleosynthesis, probably by the first stars.

Because of the prominence of lines of metals [Na, K, Ca, and Fe, for example (*40*)] in the visible wavelengths of stellar spectra, astronomers use the term "metals" to refer to the admixture of elements other than H and He. The most abundant of these "metals" is O. Many stars have a deficit of $10^{-2}$ to $10^{-5}$ of metals (*41*), relative to solar abundances; these metal-poor stars are thought to contain evidence of the first steps of galactic evolution (*42*). These star show an enhanced abundance of "alpha" elements (*43*) ($^{16}$O, $^{20}$Ne, $^{24}$Mg, $^{28}$Si, $^{32}$S, $^{36}$Ar, $^{40}$Ca, and $^{48}$Ti) relative to Fe (*44*), and possibly the signature of *r*-process elements (*4, 45–47*). This is what would be expected if these polluting nuclei were introduced into the interstellar medium (and hence into the stellar birthplaces) in order of speed of production: core collapse SNe come from the most massive stars, which evolve the fastest. Thermonuclear SNe require lower mass progenitors, and evolve slower. The competitor to the *r*-process, the *s*-process (*22*), occurs most vigorously in intermediate mass stars, which again evolve slower than massive stars.

The dwarf galaxy I Zw 18 is metal-poor (0.02 times the solar abundance). It still has massive stars, and so has undergone a burst of star formation within the last $10^7$ years (*48*). This, and its relative proximity (10 Mpc, or $3 \times 10^7$ light years), allow it to be studied in some detail. It appears to have abundances which are similar to the pattern seen in metal-poor stars (*49, 50*).

The quasi-stellar objects (QSO's) are the brightest distant objects known. Their spectra show a wealth of absorption lines, arising in gas clouds between them and Earth. Most of these clouds are far away themselves, so that the study of these lines allows us to probe gas clouds at great distance. These clouds seem to be related to, or part of, galaxies that are still early in their evolution. The clouds also show abundances which are similar to the pattern seen in metal-poor stars (*51–53*), indicating again a pattern of stellar nucleosynthesis first by core collapse SNe, and then by thermonuclear SNe and intermediate mass stars.

## Smoking Guns

Chemical analysis of meteorites (*54–58*) indicates that some grains were formed in red giant atmospheres or in expanding supernova ejecta and therefore represent presolar dust grains . These tiny grains (about 1 μm) were not reheated and destroyed when the solar system formed, and so provide us with matter that is literally stardust. Ion-probe technology has allowed isotopic abundances to be determined in such small samples. The most extensively studied grains (SiC, graphite, and diamond) are all C rich (*59*). An uncommon class (≈ 1%) of the SiC grains, called X grains, have isotopic anomalies in silicon nitride ($Si_3N_4$) mineral phase. X grains from their structure chemistry, and especially their isotopic composition, provide evidence of past thermonuclear burning. The grains show $^{28}$Si and $^{15}$N excesses relative to solar abundance, $^{13}$C excesses and deficits, and extremely high $^{26}$Al/$^{27}$Al ratios ($^{27}$Al is the nonradioactive isotope of Al). Several X grains have excesses in $^{44}$Ca, evidently from the decay of $^{44}$Ti (half-life of 52 years), as well as excesses in $^{47}$Ti, $^{48}$Ti or both. Major discrepancies exist between the predicted isotopic abundances of the spherically symmetric simulations and the observed isotopic abundances of the grains (*54–57*). Arbitrary mixing of three selected regions, without mixing of intervening layers, is required. At least part of this problem is related to the lack of a hydrodynamic treatment of convection for these simulations, so that comparable predictions from multidimensional models (Fig. 2) are needed.

The long-standing puzzle of low $^{12}$C/$^{13}$C ratios in low-mass (1 to 2 $M_\odot$) red giant branch (RGB) stars, and the recent puzzle

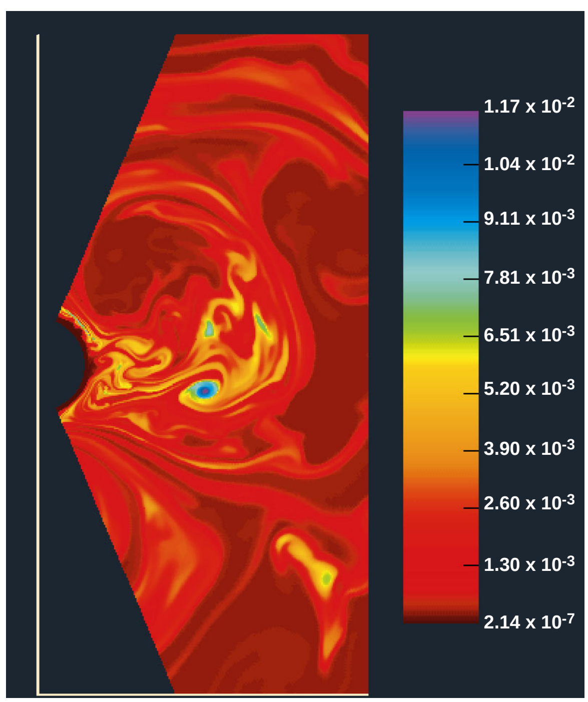


**Fig. 2.** Cross-sectional view of a sector in the oxygen burning zone of a 20 $M_\odot$ star, an hour before core collapse (*36*). The colors represent the abundance of $^{20}$Ne, which is a good tracer of the flow patterns, and which is entrained from above the outer formal boundary of the convection zone. Here violet denotes 1% by mass, and red is zero. Unlike one-dimensional simulations, the pattern is complex, and mixing is macroscopic but not microscopic.

of low $^{18}O/^{16}O$ ratios in asymptotic giant branch (AGB) stars and in circumstellar $Al_2O_3$ grains preserved in meteorites, can be resolved by deep circulation currents, extending below the standard convective envelope (*60*). This is exactly the sort of extended mixing, beyond the formal convective boundary, found in the multidimensional simulations.

The spectra of red giant stars show abundances of nuclei which can be strongly affected by extended mixing. Millimeter wavelength spectra of red giant stars (*61*) show variations of $^{25}Mg/^{24}Mg$ and $^{26}Mg/^{24}Mg$ ratios and evidence for $^{26}Al$. F is produced in intermediate mass stars (*62*). The predictions of abundances of CNO isotopes are sensitive to mixing assumptions (*63*). The globular cluster red giants show enhanced Na and Al relative interesting behavior in O, Na, and Al (*64, 65*). For all these cases, the standard simulations do not allow enough mixing of material to explain these chemical abundances or variations. A similar indication comes from a different source: the study of our sun using helioseismology (*66*). A suspected flaw in solar models is the need for some mixing below the convection zone. While stars like the sun do not eject much burned matter, this is consistent with a general feature found in the multidimensional simulations, a feature which does affect the nature of burning in massive stars.

With spectral coverage from UV to IR wavelengths by sensitive linear detectors, combined space and ground-based observations of SNe provide a history of the emitting layers of the explosion, as successive regions become transparent. As these data are better understood, it becomes possible to infer the abundances ejected, using the spectral features as diagnostics. Realistic simulations of the physics of the events are also required. This is beginning to happen (*67–70*), although there are still controversies as to the detailed nature of the events and the physics needed to simulate their explosions and spectra (*7, 68, 70–75*).

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