Stellar nucleosynthesis

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I. NUCLEOSYNTHESIS INSIDE STARS

Nuclear astrophysics started in the late 1930s, when Hans Bethe (1939) discussed both the proton-proton chain and the carbon-nitrogen cycle for turning hydrogen into helium. This conversion involves a series of nuclear reactions, but only two nuclei at a time, so the overall rate per proton is proportional to only one power of density. The next impetus to nuclear astrophysics came from the Kellogg Radiation Laboratory at Caltech, directed by Charles Lauritsen, in the late 1940s and the 1950s when William Fowler and his colleagues undertook experiments on energy releases, individual energy levels, and nuclear reaction rates. The first major impact for element production was a negative one when Fowler and his team showed that ^{8}Be is unstable, so that some triple collisions would be necessary to build up other elements from helium, and triple collisions would require very high densities. A major drama was provided by the precise position of resonant energy levels, since the typical space between levels is large in light nuclei but in the unlikely event that a level happens to lie in the appropriate narrow energy range it can increase thermonuclear reaction rates enormously. Such a level in ^{8}Be, measured by Fowler's team, was used by Salpeter in 1951 to show that the "triple-alpha reaction" can proceed fairly rapidly with $^{8}\mathrm{Be}+^{4}\mathrm{He}\rightarrow^{12}\mathrm{C}$ as the second step. In 1953 Fred Hoyle predicted at just what energy there should also be a resonance in ^{12}C to make the carbon production rate even faster, so that it could compete with the destruction rate of $^{12}\mathrm{C}+^{4}\mathrm{He}\rightarrow^{16}\mathrm{O}$. This level was soon confirmed experimentally at the right energy. Nuclear experimental data have improved enormously since the 1950s, but it is ironic that one of the biggest remaining uncertainties in nuclear astrophysics today concerns the precise parameters of a pair of resonance levels in ^{16}O, just below the thermonuclear energy range.

The interior of the sun and of unevolved, main-sequence stars, where hydrogen is converted into helium, was understood much earlier, but the interior of red giant stars was a puzzle until the early 1950s. Numerical calculations by Hoyle, M. Schwarzchild, and others finally showed that, although the surface expands when a main-sequence star evolves into a red giant, the interior heats up and contracts. The central density in extreme red giant stars (the variable stars at the "tip of the red giant branch") is sufficiently large to initiate the triple-alpha conversion of helium into carbon and oxygen (plus smaller amounts of ^{20}Ne). In the big-bang model of cosmology high temperatures can also be reached in the early universe. Alpher, Herman, and Gamow first calculated in 1949 what elements could be built up from hydrogen. The density in the early universe, when its temperature was of order 10^{8} K, was very much smaller than in red giant interiors, and little carbon and oxygen could be produced [modern primordial nucleogenesis is described in the Astrophysics and Cosmology section of this volume, while the history of controversies in the field of cosmology is treated in a book by Kragh (1996)].

The buildup of heavier elements in even more evolved stars, starting from ^{12}C, ^{16}O, and ^{20}Ne in red giant stars, consists of at least two stages: (i) The exothermic buildup of the iron region of nuclei, which have the largest binding energy per nucleon, and (ii) the much rarer, endothermic production of the very heavy nuclei, which requires some nonequilibrium catastrophic environment, such as a supernova. In reality, theorists had to consider more than two stages, with both fast and slow time scales, reprocessing in second-generation stars, etc. In spite of these complexities, the basic nuclear physics scheme for building up almost all the isotopes was already in place by the late 1950s. Two classic original papers by Burbridge, Burbridge, Fowler and Hoyle (1957) and by Cameron (1957) still serve as excellent reviews today.

While the nuclear reaction schemes *per se* were largely understood 40 years ago, embedding these schemes into quantitative stellar evolution calculations is a task that is still not fully completed. Moreover, while we know the present-day isotopic abundances in stellar atmospheres and in interstellar gas fairly well, we are only beginning to learn quantitatively what these abundances were when the universe was much younger. To illustrate the complexities with one surprising result: Although all stars start on the main sequence and produce helium in their interiors, most of the interstellar helium today was already there when the galaxy was formed, i.e., most of it is primordial and not from stars. One reason for this result is that there is little mixing from a star's center to its surface (and usually little mixing between stars and interstellar gas); another reason is that much of the interior helium is processed into heavier elements before a star dies. Furthermore, to predict today's interstellar abundances quantitatively we need to know how many stars of various masses were born and have already died, since only in old age (e.g., planetary nebulae) and death (supernovae) does the material from a star's interior reach interstellar space. This mass distribution, the "initial mass function," is still somewhat uncertain.

In spite of the pessimism of the last paragraph, much of stellar nucleosynthesis is now understood, and fortunately there are some excellent books and reviews which tell the story. We first give references to some of these (before returning to the uncertainties): The basic theory of stellar evolution is given in two textbooks (intelligible to physicists), Clayton (1968) and Kippenhahn and Weigert (1996), as well as in Iben (1991). Since most reviews and texts are written by theorists (like myself) the nuclear experimentalists often do not get enough credit, but luckily this is remedied by Rolfs and Rodney (1988). The whole present-day story of nucleosynthesis in stellar interiors and the chemical evolution of interstellar matter is given in two recent texts, Arnett (1996) and Pagel (1997), plus two collections of reviews by Prantzos *et al.* (1993) and Schramm and Woosley (1993). The following references give more details on two specialized subtopics: Clayton (1968) and Barnes *et al.* (1982) for nucleocosmochronology (ages and radioactivity); Simpson (1983) and Reeves (1994) for the very lightest isotopes and the effect of cosmic rays.

Theorists working on evolution of spherical stars used to make fun of colleagues in biophysics for inventing a spherical cow to make calculations easier. Overall deviations from sphericity in a star are still small percentage-wise, but for nuclear reactions in a highly evolved star the deviations turn out to be just about as important as for a cow: Instabilities abound for both the hydrodynamics and the nuclear burning, and stellar evolution calculations now have to be carried out with three-dimensional codes. Such calculations are about as much of a challenge to modern supercomputers as one-dimensional calculations were to early electronic computers 40 years ago. One has to consider all types of nuclear burning—laminar flames, deflagration waves, and detonation waves—but also turbulence, convective overshot, Rayleigh-Taylor instabilities, etc. Such complications are particularly severe for the catastrophic explosions in supernovae (Thielemann *et al.*, 1996). However, they are also present in somewhat less violent circumstances, such as intermediate-mass stars in the Asymptotic Giant Branch stage as they start to lose mass and evolve into planetary nebulae (Herwig *et al.*, 1997). The uncertainties about the instabilities are exacerbated by the ''onion-skin-layers'' in highly evolved stars, e.g., a Si-core, next a C, O layer, then He and then H, etc., so that a nuclear flash in one layer may (or may not) trigger nuclear burning in others.

The hydro/nuclear instabilities are likely to remain the biggest challenge for stellar evolution theory for some time, but there are two additional challenges: Some attempts at including electron Coulomb screening corrections to thermonuclear reaction rates have been made for over 40 years, but the required nonequilibrium plasma physics is still not understood sufficiently well. In spite of a recent review article (Brown and Sawyer, 1997), the controversies continue and probably will have to be tackled with very extensive numerical calculations. What stellar evolution and nucleosynthesis were like when the universe and our Galaxy were young is now starting to be explored (see Pei and Fall, 1995). Since isotope abundance ratios are different for medium-mass and very massive stars, there is even a chance that we shall learn how the initial mass function has changed with time.

II. NUCLEAR REACTIONS IN WHITE DWARF AND NEUTRON STAR SURFACES

Most of the medium-heavy and heavy elements in interstellar space were made in the deep interior of evolved stars and were then ejected from the surface, but some surface reactions are also of interest. Some fraction of stars have a close companion star that sheds mass, which then accretes onto the surface of the first star. The accreted material is mostly unprocessed, i.e., it consists mainly of hydrogen and helium which can burn if compressed to sufficiently high density and temperature. If the star is a white dwarf, its radius is small and its surface gravity is large, so the compression is achieved fairly rapidly; even more so on the surface of a neutron star, which has an even smaller radius. One should then expect some kind of relaxation oscillation: the hydrogen and helium build up until some kind of nuclear explosion burns up this fuel and gives a pulse of greatly increased luminosity, followed by another quiescent period while the hydrogen and helium build up again, etc. The accretion rate varies with time, and the flashes should be recurring but not accurately periodic.

The so-called ''classical nova'' is caused by such accretion onto a white dwarf star, followed by ignition of hydrogen burning by the C, N, O cycle plus a ''nuclear runaway'' (see Truran's report in Barnes *et al.*, 1982). The white dwarf atmosphere, before the accretion, could in principle consist of helium but often has some kind of mixture of C, O, and Ne. The details of the nuclear flash depend on the atmospheric composition and on the white dwarf's mass (see, for example Nofar *et al.*, 1991).

Rapidly rotating, magnetic, and isolated neutron stars often exhibit the pulsar phenomenon and a slight mass loss from the surface, but less extreme neutron stars that have a close companion star can accrete matter instead. This accretion can lead to nuclear flashes, as it does for an accreting white dwarf, but the details are different because of the smaller radius and even stronger gravitational field. For instance, the luminosity is emitted in x rays, and the steady luminosity between flashes, from the gravitational accretion energy, is larger than the averaged energy from the nuclear burning (Joss and Rappaport, 1984). The detailed shape of the x-ray bursts, produced by the thermonuclear flash, is particularly complex and depends strongly on the accretion rate. The complexity is partly due to the fact that both hydrogen and helium can be ignited, and the two burning shells interact with each other. Furthermore, the intrinsic burning time is shorter than the sound propagation time around the star's surface, and one can have localized ignition with the fire then spreading around the surface in some irregular manner (Bildsten, 1998). These x-ray bursts are also no more spherical than a cow and insight gained into instabilities from neutron star surfaces may well help to understand stellar evolution better.

This essay does not deal at all with neutron star interiors, nor with supernovae, but a few references may be useful: the book by Arnett (1996) deals with supernovae, the book by Tamagaki *et al.* (1992) with neutron stars in general. Two papers with references are Kalogera and Baym (1992) and Nomoto *et al.* (1997).

III. SUMMARY

The main outline of nucleosynthesis inside stars is now understood and is an essential tool in interpreting observed chemical abundances in terms of the evolution of stellar populations in galaxies. However, electron Coulomb screening corrections to thermonuclear reaction rates are still uncertain. Beyond that are the instabilities which occur in nuclear burning stars like supernovae, asymptotic giant branch stars, and accreting neutron stars, which require three-dimensional dynamic simulations on supercomputers. Only such calculations can yield reliable results on chemical abundances that can be compared with observations.

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