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

Synthesis of the Elements in Stars: B^2FH and Beyond

E. MARGARET BURBIDGE
University of California, San Diego

1.1 Introduction

Fred Hoyle was the H in the alphabetically listed authors of the long paper (Burbidge et al. 1957) on building the chemical elements through nuclear reactions occurring during the evolution of stars in our Galaxy. But this work had its origin 11 years earlier, in the seminal 40-page paper by Fred Hoyle, which was presented at a meeting of the Royal Astronomical Society in London on November 8, 1946. That paper was entitled "The Synthesis of the Elements from Hydrogen" (Hoyle 1946). I have never forgotten the experience of listening to Fred giving this exciting account of his work on building the elements in the abundance peak around iron, where statistical equilibrium would prevail in high-temperature, high-density interiors of evolved stars.

This was indeed a seminal paper. Work on the composition of the Sun's atmosphere had provided data on the relative abundances of the elements, available before its publication by Hans Suess and Harold Urey (see, e.g., Suess & Urey 1956), and Fred had noticed that there was a peak in the abundances of the elements centered on iron, where he knew the packing fraction, or binding energy per nucleon, reached a maximum, making such elements stable at high temperatures and pressures. Color-magnitude diagrams of stars in various clusters, from the work of Allan Sandage, had given information on the evolutionary tracks of the stars of different masses when they leave the main sequence, so Fred was free to calculate what would happen when stars reached the end of the observed tracks.

Fred Hoyle's 1946 paper came at a time when the current theory was that the elements were created primordially by the coagulation of neutrons just after the birth of the Universe. It was something of a joke that such a process would meet with trouble at masses 5 and 8, there being no stable elements here. Gamow, always ready with diagrams and drawings to illustrate his work, drew pictures of two ditches at masses 5 and 8, with himself jumping over them. George Gamow, Maria Goeppert-Mayer, and Edward Teller were working at that time on this primordial agglomeration of neutrons, in spite of the difficulty at masses 5 and 8.

1.2 Iron-peak Elements and Supernovae

But it was Hoyle who realized the significance of the peak in the abundances of the elements centered on iron, and stretching from nuclear mass number $A \simeq 40$ to $A \simeq 60$, containing the isotopes of elements from Ca to Zn. A modern discussion of what B^2FH named the *e*-process (*e* for equilibrium), is given by Bradley Meyer in the publication by Wallerstein et al. (1997). There is a section entitled "The e-Process and the Iron-Group

Nuclei" by Meyer which gives many references both to the physics involved and to work on supernovae, relating this to the decays of the various isotopes involved in the physics of supernova explosions. Supernovae were the locations described in B^2FH as the sites of the *r*-process. That section, in Meyer's account, referring to the excess abundance of ^{44}Ca found in graphite and silicon carbide grains in primitive meteorites, ends with the words: "In 1957, B^2FH could only have dreamed of having such tangible evidence of element formation in stars!"

1.3 Paul Merrill and Technetium

Actually, we had astrophysical evidence—not "tangible," but very clear-cut—for the location of the *s*-process, in which heavier elements are built from lighter ones by the successive captures of neutrons. We named this the *s*-process, "*s*" for "slow," because after each neutron capture that produces an unstable element, there is time for that element to β-decay before capturing another neutron. The clue for the location of the *s*-process came in a landmark Mt. Wilson 1952 paper by Paul W. Merrill—he identified spectroscopic evidence for the unstable element technetium in certain red giant stars (Merrill 1952), stars of class S. With a half-life of $\sim 10^5$ yr*, technetium obviously had to be produced actually in these red giant stars, and then mixed to the surface. We could therefore see such stars as the astrophysical locations where free neutrons must be produced and made available in an interior region, and, after their capture by Fe-peak elements, the products mixed to the stellar surface.

Stars in the relatively stable phase of stellar evolution along the asymptotic giant branch provide a location for the occurrence of the *s*-process. In B^2FH we had as an analogy the flow of water over a riverbed with deep holes in it. Water flowing along and encountering such holes would accumulate there until the hole was filled, when it would flow on to the next hole. The relevant time scale between neutron captures was $\sim 10^5$ yr. The flux of neutrons was represented by the flow of water, and the holes were represented by nuclei with closed shells, at the "magic numbers" of Maria Goeppert Mayer's shell model of nuclei.

During the work of the four of us, we realized that it would be a good idea to get high-dispersion spectra of a star showing evidence for the occurrence of the *s*-process, and determine the abundances of the elements in this and in a standard star for comparison. Merrill's stars of type S would be good, but we knew from our recent work on abundance determination in stars that the analysis of such cool stars would be a real problem. We knew, however, from work by W. Bidelman, that a class of stars known as Ba II stars, seeming to have an overabundance of the element barium, formed in the *s*-process could provide the evidence we needed.

Looking through the literature, we picked the star HD 46407. Geoff, as a Carnegie Fellow, was entitled to apply for observing time on Mt. Wilson. Women, in those far-off days, were not allowed on Mt. Wilson, but, through the persuasive efforts of Willy Fowler and Allan Sandage, Director Ira S. Bowen gave permission for me to accompany Geoff who was awarded time on both the 60-inch and the 100-inch telescopes, as long as we used our own transportation, lived in the summer cottage—the Kapteyn Cottage—instead of in the dormitory called the Monastery, and brought our own food.

The Table shows the results that Geoff and I published (Burbidge & Burbidge 1957). The

* The longest lived isotope of technetium, ^{98}Tc, has a half-life of 4.2×10^6 yr, whereas the isotope formed in the *s*-process is ^{99}Tc, which has a half-life of 2×10^5 yr.

Table 1.1. *The s-Process Ba II Star HD 46407*†

Element	Atomic Weights, *s*-Isotopes	y'	$\langle \sigma \mathrm{N} \rangle y'$
Strontium	86, 87, 88	4.7	381
Yttrium	89	7.8	1326
Zirconium	90, 91, 92, 94	4.9	884
Niobium	93	5.2	832
Molybdenum	95, 96, 97	4.8	343
Barium	134, 136, 138	14.9	281
Lanthanum	139	9.8	647
Cerium	140	10.7	407
Praseodymium	141	28.0	672
Neodymium	142, 143, 144, 145, 146	15.7	443
Tungsten	182, 184	13.0	914

†Burbidge & Burbidge (1957)
σ = neutron capture cross-section
N = solar system abundance
y = observed overabundance
y' = overabundance ratio of isotopes built by *s*-process alone
Within a factor$\sim$2, $\langle \sigma \mathrm{N} \rangle y'$ is constant: mean $\langle \sigma \mathrm{N} \rangle y'$ = 648

elements listed, strontium to tungsten, are elements with one or more isotopes made in the *s*-process. From our observed overabundance, y, for these elements, we used the emerging calculations from $\mathrm{B^2FH}$ to calculate y', the observed overabundance of isotopes built by the *s*-process alone. We used recently available neutron capture cross-sections, σ, to calculate the product $\langle \sigma \mathrm{N} \rangle y'$, and, despite the fact that the cross-sections were not very accurate (they were substantially improved soon afterwards), the product $\langle \sigma \mathrm{N} \rangle y'$ was found to be constant to within a factor $\sim$2.

1.4 Recent Work

With the large telescopes and modern instruments available today, the progress of unraveling the details of nucleosynthesis after stars leave the main sequence is one of the most exciting branches of astrophysics. Stars of very low Fe abundance can now be picked out in the halo of the Galaxy, and the study of *r*-process elements there are giving information on the early stellar population and the seeding of the young Galaxy with the products of early supernovae (e.g., Sneden et al. 1998).

But the *s*-process is also yielding very interesting data on stellar evolution. The astronomers working with the 3.6 m telescope of the European Southern Observatory observed a group of same-temperature CH (carbon rich) evolved stars, and found that the line Pb I λ4057.31 is clearly visible and quite strong in three but absent in one. Pb is the last stable element produced in the slow neutron capture chain of nucleosynthesis (Van Eck et al. 2001). Such observations will surely go hand-in-hand with the theoretical work on the late evolutionary stages of stars, and build our knowledge of the history of the Galaxy.

References

Burbidge, E. M., & Burbidge, G. R. 1957, ApJ, 126, 357
Burbidge, E. M., Burbidge, G. R., Fowler, W. A., & Hoyle, F. 1957, Rev. Mod. Phys., 29, 547
Hoyle, F. 1946, MNRAS, 106, 343
Merrill, P. W. 1952, Science, 115, 484
Sneden, C., Cowan, J. J., Burris, D. L., & Truran, J. W. 1998, ApJ, 496, 235
Suess, H. E., & Urey, H. C. 1956, Rev. Mod. Phys., 28, 53
Van Eck, S., Goriely, S., Jorissen, A., & Plez, B. 2001, The Messenger, 106, 37
Wallerstein, G., et al. 1997, Rev. Mod. Phys., 69, 995