
ELSEVIER
ISSN 1387-6473
New Astronomy Reviews
Editors
Jean Audouze
Institut d'Astrophysique, Paris
Peter S. Conti
University of Colorado
Ken'ichi Nomoto
University of Tokyo
Alfonso G. Cavaliere
Università di Roma "Tor Vergata"
Jack J. Lissauer
NASA AMES Research Center
Ralph A.M.J. Wijers
University of Amsterdam
Philip A. Charles
South African Astronomical Observatory
Available online at
ScienceDirect
www.sciencedirect.com
http://www.elsevier.com/locate/newastrev
Volume 52, Numbers 7–10, October 2008
Astronomy with Radioactivities. VI
edited by: R. Diehl, D.H. Hartmann, N. Prantzos

New Astronomy Reviews 52 (2008) 360–363

Contents lists available at ScienceDirect

New Astronomy Reviews

journal homepage: www.elsevier.com/locate/newastrev

Fred Hoyle, primary nucleosynthesis and radioactivity

Donald D. Clayton *

Kinard Laboratory, Physics and Astronomy, Clemson University, Clemson, South Carolina 29634, United States

ARTICLE INFO

Article history:
Available online 1 July 2008

ABSTRACT

Primary nucleosynthesis is defined as that which occurs efficiently in stars born of only H and He. It is responsible not only for increasing the metallicity of the galaxy but also for the most abundant gamma-ray-line emitters. Astrophysicists have inappropriately cited early work in this regard. The heavily cited B^2FH paper (Burbidge et al., 1957) did not effectively address primary nucleosynthesis whereas Hoyle (Hoyle, 1954) had done so quite thoroughly in his infrequently cited 1954 paper. Even B^2FH with Hoyle as coauthor seems strangely to not have appreciated what Hoyle (Hoyle, 1954) had achieved. I speculate that Hoyle must not have thoroughly proofread the draft written in 1956 by E.M. and G.R. Burbidge. The clear roadmap of primary nucleosynthesis advanced in 1954 by Hoyle describes the synthesis yielding the most abundant of the radioactive isotopes for astronomy, although that aspect was unrealized at the time. Secondary nucleosynthesis has also produced many observable radioactive nuclei, including the first gamma-ray-line emitter to be discovered in the galaxy and several others within stardust grains. Primary gamma-ray emitters would have been even more detectable in the early galaxy, when the birth rate of massive stars was greater; but secondary emitters, such as ^{26}Al, would have been produced with smaller yield then owing to smaller abundance of seed nuclei from which to create them.

1. History of the theory of nucleosynthesis and Hoyle's equation

In 1954 Hoyle (Hoyle, 1954) described in detail ideas having far reaching application to the origin of the set of abundant isotopes that can be produced in stars made of H and He—what is now called *primary nucleosynthesis*. These include the most abundant isotopes of each chemical element from carbon to nickel. Hoyle subtitled his foundation paper (Hoyle, 1954). "The synthesis of elements from Carbon to Nickel". By contrast, B^2FH(Burbidge et al., 1957) contributed creatively to the *secondary processes* of nucleosynthesis, those which change one heavy nucleus into another within stars but which do not increase the metallicity of the galaxy as it ages. Secondary nucleosynthesis occurs by using heavy seed nuclei that were present initially within the dominant H and He of stars. These are transformed to other heavy nuclei as byproducts of the nuclear reactions that occur during the star's evolution—for example, making ^{14}N from initial C and making ^{26}Al from initial Mg. The secondary processes stimulated observational astronomy owing to being more easily observable at the telescope within individual stars than were the more difficult observations of metallicity in old metal-poor stars. This curiosity accounts in part for B^2FHbeing the more celebrated paper and having very many more citations than Hoyle's more fundamental paper. I have expressed sociological reasons for B^2FH to have supplanted Hoyle's paper in scientific consciousness in my presentation "B^2FH: What they did, and did not" (<http://www.na2007.caltech.edu/program2.html>) at the Caltech international conference (<http://www.na2007.caltech.edu/>) which was convened to celebrate joint semicentennials of two ground-breaking 1957 publications (Burbidge et al., 1957;Cameron, 1957) in nucleosynthesis. Those two papers have been cited vastly more often than Hoyle's for the beginnings of the general theory of nucleosynthesis in stars, often serving as a default reference for nucleosynthesis in stars. I stress here that citation trend should be reversed by astronomers understanding what Hoyle (Hoyle, 1954) achieved in 1954.

The nucleosynthesis of our chemical elements is one of the grand theories of science, and gamma-ray-line astronomy affords unique tests of its ideas. I have constructed the equation that encapsulates Hoyle's paper, what I call *Hoyle's equation* (Clayton, 2007), from a careful reading of his 1954 paper (Hoyle, 1954). His statements and quantitative calculations point clearly to ideas of nucleosynthesis in stars that he was advancing for the first time and that are more sweeping than detail-oriented sequels. Hoyle's discussion is phrased in terms of the mass Δm_{new} of new primary isotopes that are ejected from massive stars. His basic approach to stellar nucleosynthesis is to calculate that rate of injection into the ISM.

$$\mathrm{d}m_{new}/\mathrm{d}t = H^{nucl} \tag{1}$$

where $H^{nucl} = B(t')\mathbf{Ev}(t'-t)\Sigma_k \Delta m_k$ is the "Hoyle nucleosynthesis rate". $B(t')$ is the stellar birthrate of stars having total mass such that they evolve to end their lives at time t, $\mathbf{Ev}(t',t)$ is an operator (rather than a number) that expresses the nuclear and stellar evolution that

* Tel.: +1 864 882 8061.
E-mail address: claydonald@gmail.com

1387-6473/$ - see front matter
doi:10.1016/j.newar.2008.05.007

occurs during its lifetime from t' to t, and Δm_k is the mass of isotope k ejected at time t. Then a sum over all presolar birthdates t' selects the appropriate stellar masses for each birthdate. Realize that stellar evolution was only dimly perceived in 1953 when Hoyle wrote this paper. The structure of red giants was its current literature frontier, and Hoyle's innovative work on that problem had qualified him as the leading expert on its ideas. Hoyle's equation is the form that Eq. (1) becomes when using Hoyle's outline (Hoyle, 1954) of the complete evolution of massive stars.

The synthesis of elements from carbon to nickel in massive stars occur through a series of core evolutions that Hoyle laid out (Hoyle, 1954) for the first time. He explained that gravitational contraction causes temperature increases after each nuclear fuel is consumed, and he described the nuclear burning during each advanced core evolution. Because those massive stars all evolve almost instantaneously in comparison with galactic timescale, Hoyle takes $B_{M>}(t)$ to be the birthrate of all such massive stars at time t, and it clearly equals their death rate at the same time if the numbers of stars are to change only slowly. The subscript M> characterizes stars too massive for their cores to become stable white dwarfs, roughly greater than ten solar masses. Hoyle predicted that collapse of those final central evolved cores is inevitable. The matter outside the cores is presumably ejected in the supernova phenomenon. So for those massive stars that were the burden of his paper, Hoyle's equation expresses the rate of ejection of new primary isotopes from C to Ni (Clayton, 2007) as

$$\mathrm{d}m(\mathrm{C}-\mathrm{Ni})/\mathrm{d}t = B_{M>}(t)\mathbf{Ev}^{\mathrm{nucl}}\Sigma_k \Delta m_k \quad (2)$$

Hoyle attributed the mass and identity k of new primary isotopes ejected per massive star to the following successive core burning phases: ^{12}C and ^{16}O from core He burning; ^{20}Ne, ^{23}Na, and ^{24}Mg from subsequent core C burning; additional ^{16}O and ^{24}Mg from Ne burning; ^{28}Si and ^{32}S from core O burning; ^{32}S, ^{36}Ar and ^{40}Ca from photoalpha reactions on ^{32}S and heavier alpha nuclei during later heating of the O-exhausted core; and finally ^{52}Cr, ^{56}Fe, ^{60}Ni from subsequent nuclear statistical equilibrium. Hoyle was not able to calculate the shrinkage of the core mass yielding the familiar onionskin structure of our models; but he did anticipate that cores would become smaller based on his calculations of red giants. He presciently observed that neutrino emission would govern the collapse timescale when core temperature exceeds $T = 3 \times 10^9$ K, greatly speeding collapse. Because these ideas are so familiar today it is easy to glide over them without realizing their farsightedness in 1954. All of these ideas stem from Hoyle's paper (Hoyle, 1954).

Hoyle's equation expresses a breathtakingly modern view of the metallicity-increasing nucleosynthesis during galactic history. Hoyle missed only the full photonuclear quasiequilibrium (Bodansky et al., 1968) during Si burning and the n/p details of the NSE (Clayton, 1999). But his equation, given above, remains correct today. Hoyle's equation has required much modern work to determine the Hoyle nuclear evolution H^{nucl}. Countless computed evolutions for the massive stars have striven continuously for more realistic formulations and for more secure calculations of the set Δm_k. It is unfortunate that most modern work seems not to have realized that it is evaluating Hoyle's equation. Hoyle did not actually write that equation, although he easily could have; but he did envision and described its factors. Had he written the equation, clearer scientific visibility of his unparalleled achievement would have followed more easily, and the relative citations of (Burbidge et al., 1957; Hoyle, 1954) by later workers would have been reversed.

2. Radioactive progenitors and primary nucleosynthesis

About forty years ago we initiated at Rice University a computational program to evaluate Hoyle's equation. Similar work had already begun at Yale by Al Cameron, who was also inspired (Cameron, 1957) by Hoyle's paper (Hoyle, 1954). Fig. 2 shows our result (Woosley et al., 1973). For those calculations we had assumed that the process of ejecting Hoyle's shells would shock parts of each to higher temperature than experienced in hydrostatic burning and that each would quickly cool with a timescale that we estimated in a reasonable way. Fig. 2 displays the set Δm_k from the summation of exactly three shocked shells surrounding the collapsed core: (a) a shell of oxygen shocked to peak temperature $T_9 = 3.6$; (b) a more central shell heated more strongly by the shock to $T_9 = 4.7$; (c) a still more central shell shocked to $T_9 = 5.5$, adequate to completely burn the ^{28}Si and experience an alpha-rich freezeout (Woosley et al., 1973) characterized by a large free-alpha-particle excess. The sum of these three sets Δm_k is shown in Fig. 1 after their sum has been normalized at ^{28}Si to the solar abundances. Importantly, the neutron excess was in each case 0.2% of the number of protons, almost all of which was generated from the initial CNO abundances, for which (Woosley et al., 1973) used a solar concentration. Those seed CNO nuclei had been converted to ^{22}Ne prior to the shock arrival. The first step occurs via the radiative capture reaction ^{14}N$(\alpha,\gamma)^{18}$F during He burning, which creates a fundamentally important radioactive nucleus. The weak decay of ^{18}F to ^{18}O changes a mass-18 nucleus having equal numbers of protons and neutrons to a daughter nucleus having two excess neutrons. The neutron excess established by that decay is *secondary* rather than *primary* because its value derives from the initial abundances of C and O. Neutron excess is required for the synthesis of neutron-rich isotopes of the light elements (e.g. ^{18}O, ^{22}Ne, ^{26}Mg, ^{30}Si etc.). Its value would have been smaller in the earliest stars, in which case the abundances of neutron-rich isotopes produced would have been smaller. In that sense, the neutron-rich isotopes are to considerable degree *secondary*, as Fig. 24 of (Woosley et al., 1973) shows clearly.

In 1971 it was immediately evident from Fig. 1 that the solar abundances had been spectacularly reproduced. The O-burning shell (a) had been responsible for the isotopes ^{28}Si and ^{32,33,34}S, ^{35,37}Cl, ^{36,38}Ar ^{40,42}Ca and ^{50}Ti; the shell of incompletely burning Si (b) had been responsible in the summation for about half of the alpha-isotopes isotopes ^{28}Si, ^{32}S, ^{36}Ar and ^{40}Ca and for isotopes ^{48,49}Ti, ^{51}V, ^{50,52,53}Cr, ^{54}Fe and about one-third of the ^{56}Fe. The alpha-rich freezeout had been responsible in the summation for

Fig. 1. Fred Hoyle on the Caltech campus in February 1967. The now destroyed dome of historic Throop Hall rises poetically behind him. Hoyle has just invited the author to participate in the five-year authorization of his Cambridge Institute of Theoretical Astronomy. At the time of this photograph we were discussing the newly discovered (Bodansky et al., 1968) quasiequilibrium that governs silicon burning, a quasiequilibrium that Hoyle had dimly perceived in his picture (Hoyle, 1954) of primary nucleosynthesis. Photo by the author.

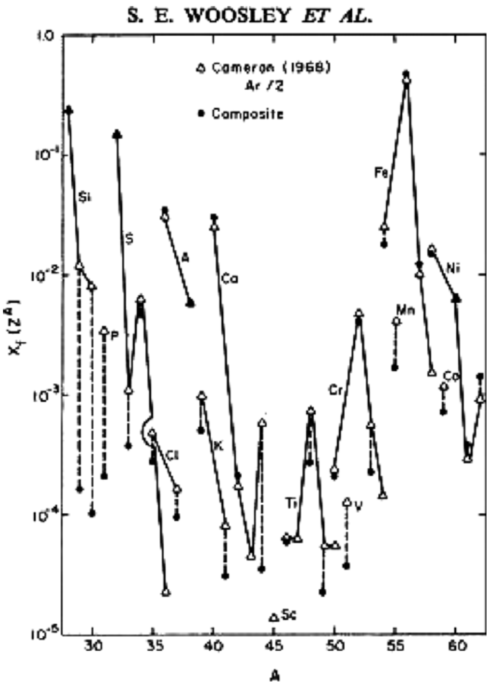

Fig. 2. The isotopic yield Δm_k from three shocked shells surrounding the collapsed core of a massive star: (a) a shell of oxygen shocked to peak temperature $T_9 = 3.6$; (b) a more central shell heated more strongly by the shock to $T_9 = 4.7$; (c) a still more central shell shocked to $T_9 = 5.5$, adequate to completely burn the ^{28}Si and create an alpha-rich freezeout (Woosley et al., 1973). The sum of these three sets Δm_k is compared with solar abundances after normalization at ^{28}Si. Figure from (Woosley et al., 1973).

almost all of the ^{56,57}Fe, ^{59}Co and ^{58,60,61,62}Ni. Fig. 1 sums their contributions. The most glaring deficiency of these computed abundances is that of ^{44}Ca. Still it was clear that ^{44}Ca must be produced as a result of the decay of abundant ^{44}Ti. Clearly a larger alpha-rich freezeout component would be needed. The ^{44}Ti abundance, which falls dramatically as the temperature declines following explosive burning, grows again at the end as the excess alphas create new ^{12}C nuclei by triple-alpha reaction which then capture a chain of alphas up to radioactive ^{44}Ti. Coulomb repulsion stops the capture chain at ^{44}Ti! The alpha-rich freezeout is a multifaceted process.

Of noteworthy interest for astronomy with radioactivity, the low neutron excess of the bulk matter ensures that many abundant isotopes were synthesized and ejected as radioactive progenitors. This would be impossible at larger neutron excess, as in secondary nucleosynthesis or in the neutron-rich *e* process of B^2FH (Burbidge et al., 1957). These radioactive progenitors include ^{41}Ca (for ^{41}K), ^{44}Ti (for ^{44}Ca), ^{49}V (for ^{49}Ti), ^{53}Mn (for ^{53}Cr), ^{55}Co (for ^{55}Mn) ^{56}Ni (for ^{56}Fe), ^{57}Ni (for ^{57}Fe), ^{59}Ni (for ^{59}Co). Each has observable effects for the sciences of astronomy with radioactivity; either as source for gamma-ray-lines from individual young supernovae (Clayton et al., 1969), or as cause of extinct radioactivity in the early solar system (Clayton, 2003), or as extinct radioactivity in that component of presolar *stardust*that condensed (Clayton and Nittler, 2004;Clayton et al., 1997) within the interior during supernova expansions. ^{56}Ni, ^{57}Ni, and ^{44}Ti were the first three progenitors of gamma-ray-line emitting nuclei to be detected from young supernovae. The first two led to new explanations of effects in supernova light curves; and ^{44}Ti observations (or lack of same) present today perplexing issues for astronomy (The et al., 2006) concerning the high abundance of ^{44}Ca. The quasiequilibrium (QSE) that explains these results during Si burning was not discovered until 1968 (Bodansky et al., 1968). That QSE was, however, a logical extension of the discussion by Hoyle (Hoyle, 1954) of the decreasing separation energies of alpha-particles and of increasing (γ,α) rates with increasing A > 28. The QSE successfully explains abundance agreements in Fig. 1 and makes it certain that in massive stars ^{56,57}Fe was synthesized as radioactive ^{56,57}Ni and ^{44}Ca as radioactive ^{44}Ti. On several occasions I conversed with Hoyle about his and Fowler's maintaining for a decade the neutron-rich *e*-process picture described by B^2FH; and his reaction was "I should have switched sooner"(Clayton, 1999;Conversations with Hoyle in Cambridge, 1975). After 1968 he believed that the gamma-ray lines derived from ^{56}Ni would be detected (Conversations with Hoyle in Cambridge, 1975). The carrying out of Hoyle's ideas and the evaluation of Hoyle's equation by many researchers yielded a cornucopia for the astronomy of radioactivity.

3. Secondary nucleosynthesis and astronomy with radioactivity

The first discovered gamma-ray-line from nucleosynthesis of radioactivity was instead the 1.81 MeV line following ^{26}Al decay (Mahoney et al., 1984). It was brilliantly exploited by the COMPTEL instrument team (Diehl, 1994) to localize galactic nucleosynthesis during the past 10^6 yr. Despite ^{26}Al having been previously documented as an extinct radioactivity (Lee et al., 1977) in primitive solar system samples and quickly thereafter having been incorrectly interpreted (Clayton, 1975, 1977) as fossil ^{26}Mg within supernova stardust, I had discounted the chance of its astronomical detectability because its yield in primary nucleosynthesis was argued by me to be too small (Clayton, 1984). However, I had failed to see that it would be the secondary nucleosynthesis of ^{26}Al by (p, γ) reactions with initial ^{25}Mg in the shells of massive stars that would be responsible for its detectable ISM abundance. Ramaty and Lingenfelter (Ramaty and Lingenfelter, 1977) had no such reticence in suggesting that the 1.81 MeV line be sought. Even so, understanding the surprisingly large ^{26}Al interstellar abundance required an improved theory of galactic chemical evolution in order to understand (Clayton et al., 1993) why the present interstellar ^{26}Al/^{27}Al ratio should be a factor $(k+1)$=4–5 larger owing to past galactic infall of low-metallicity gas than it would have been in a closed-box model. I have always seen irony in secondary nucleosynthesis producing the first measurable interstellar concentration of a radioactive nucleus, and somewhat foolish for discounting it on incomplete theoretical grounds.

Hoyle (Hoyle, 1954) had also discussed the idea of secondary nucleosynthesis of those nuclei whose created abundance derives from initial seed nuclei. He emphasized especially ^{14}N, ^{18}O, ^{19}F and ^{22}Ne in that regard, each of which depends on the initial abundances of primary C and O nuclei. Their yields do not obey Hoyle's equation but instead are proportional to the initial metallicity of each star. Hoyle also first noted that ^{22}Ne would be a source of free neutrons; indeed, it is today their major source in burning shells of massive stars (The et al., 2000), although that insight is usually attributed to later emphasis by Cameron.

Stardust has provided altogether new relationships between extinct radioactivity (in the stardust grains rather than in the early solar system) and secondary nucleosynthesis. *Stardust* is a scientific name for that small component of interstellar dust that had thermally condensed from hot stellar vapor as it cooled by expansion (Clayton and Nittler, 2004). I call attention to only silicon-carbide stardust. The two heavier isotopes of silicon are both secondary, deriving ultimately from the initial CNO abundances in the star. So increasing metallicity in new stars owing to galactic chemical evolution should temporally correlate with ^{29,30}Si excess (Clayton, 1988;Timmes and Clayton, 1996). But in the mainstream SiC, that expectation seems to go awry. The presolar AGB donor stars have greater ^{29,30}Si abundances (relative to that of ^{28}Si) than does the later formed sun (Clayton and Nittler, 2004). This astonishing discovery has forced far reaching interpretations (Clayton and Nittler, 2004) of its cause. These same AGB donor stars condensed large concentrations of radioactive ^{26}Al and ^{99}Tc in stardust SiC, judging from excess ^{26}Mg and ^{99}Ru within them (Savina et al., 2004). Type X SiC, stardust condensed within expanding supernova interiors, on the other hand, reveals evidence of an even larger suite of extinct radioactivity. Radioactive ^{26}Al, ^{41}Ca, ^{44}Ti and ^{49}V nuclei decaying within the SiC after condensation of supernova stardust produced excess daughter abundances within these grains (Clayton and Nittler, 2004;Clayton et al., 1997) and references therein). The sizes of ^{26}Mg and ^{44}Ca abundances (relative to those of primary ^{24}Mg and ^{40}Ca) imply especially large production ratios for ^{26}Al/^{27}Al and ^{44}Ti/^{48}Ti in the interior supernova zones wherein the condensation occurred. Because that condensation must occur prior to molecular-scale mixing within the supernova, which would require a much longer time, it has inspired theories of carbon condensation within hot oxygen-rich gas (Clayton et al., 1999;Clayton et al., 2001). Meteoritic chemists had thought C condensation within O-rich hot gas to be impossible on grounds of equilibrium; however, the kinetic paths lie far from equilibrium (Clayton et al., 2001). So the challenges and the consequences of extinct radioactivity in stardust have proven to be great, and their questions will not be quickly solved. When they have been solved, rich new insights into supernovae and nucleosynthesis will follow.

4. Improving astrophysicists' citations of nucleosynthesis history

Hoyle (Hoyle, 1954) can today be seen more clearly than citation rates indicate to be one of the landmark papers within the history of astrophysics. It was every bit as original and far reaching as his 1946 paper (Hoyle, 1946) that advanced a nuclear statistical equilibrium (NSE) for the origin of the iron peak. The 1954 paper predicted and calculated the nucleosynthesis of the primary elements from carbon to nickel and the associated increase of the galactic metallicity. He achieved this by predicting the nuclear evolution of the massive star cores leading up to that NSE. Undercitation of this paper would not have occurred had it not been for three things: first, Hoyle's not writing Eq. (2), which he clearly described verbally, for evaluating the rate of growth of the heavy-element mass in the ISM; second, the publication of B^2FH (Burbidge et al., 1957) three years later diverting astronomical attention toward the secondary processes of heavy-element nucleosynthesis by neutron capture; and third, a carelessness among nucleosynthesis experts in citing B^2FH almost by default, even when unfamiliar with the fundamental contents of either paper. This harsh criticism applies to me as well as to others. I have corrected the first cause by a recent perspective in *Science* (Clayton, 2007) that first displayed Hoyle's equation, constructed from his text and calculations, and by emphasizing its correctness and relevance. The second can be cured by practicing scientists distinguishing between nucleosynthesis that increases galactic metallicity and that which affects only nuclear transmutations within given stars. The third can be cured by the community understanding more clearly what B^2FH achieved and what Hoyle achieved, and by being more circumspect in their attribution of credit. In particular B^2FH made no significant advance in the synthesis of the primary elements but instead presented a more confusing and fragmentary description of it—namely, their so-called "alpha process". This problem with $B^2FH$is likely to have occurred because Hoyle did not carefully proofread that section of the manuscript.[1]

As far as the astronomy with radioactivity is concerned, both primary and secondary nucleosynthesis is involved in the set of observable radioactive isotopes. Hoyle's prescription for primary nucleosynthesis led to the most abundant gamma-ray-line emitters, but he also described the concept of secondary nucleosynthesis that is responsible for several others.

References

Bodansky, D., Clayton, D.D., Fowler, W.A., 1968. Nuclear quasiequilibrium during silicon burning. ApJ (Suppl. 16), 299.

Burbidge, E.M., Burbidge, G.R., Fowler, W.A., Hoyle, F., 1957. Synthesis of the elements in stars. Rev. Mod. Phys. 29, 547–650.

Cameron, A.G.W., 1957. Stellar evolution, nuclear astrophysics, and nucleogenesis, CRL 41, Chalk River, Ontario.

Clayton, D.D., 1975. ^{22}Na, Ne-E, extinct radioactive anomalies and unsupported ^{40}Ar. Nature 257, 36–37.

Clayton, D.D., 1977. Cosmoradiogenic ghosts and the origin of CaAl-rich inclusions. Earth Planet. Sci. Lett. 35, 398–410.

Clayton, D.D., 1984. ^{26}Al in the interstellar medium. ApJ 280, 144–149.

Clayton, D.D., 1988. Isotopic anomalies: chemical memory of galactic evolution. ApJ 334, 191–195.

Clayton, D.D., 1999. Radiogenic iron. Meteor. Planetary Sci. 34, A145–A160.

Clayton, DD., 2003. Isotopes in the Cosmos. Cambridge University Press, Cambridge. see Glossary p. 285–290.

Clayton, D.D., 2007. Hoyle's Equation. Science 318, 1876–1877.

Clayton, D.D., Nittler, L.R., 2004. Astrophysics with presolar stardust. ARA&A 42, 39–78. See also (11).

Clayton, D.D., Colgate, S.E., Fishman, G.J., 1969. Gamma-ray lines from young supernova remnants. ApJ 155, 75.

Clayton, D.D., Hartmann, D.H., Leising, M.D., 1993. On ^{26}Al and other short-lived interstellar radioactivity. ApJ 415, L25–L29.

Clayton, D.D., Amari, S., Zinner, E., 1997. Dust from supernovae. Ap&SS 251, 355–374.

Clayton, D.D., Liu, W., Dalgarno, A., 1999. Condensation of carbon in radioactive supernova gas. Science 282, 1290–1292.

Clayton, D.D., Deneault, E.-N., Meyer, B.S., 2001. Condensation of carbon in radioactive supernova gas. ApJ 562, 480–493.

Conversations with Hoyle in Cambridge, Dockray and Houston, 1968–1975.

Diehl, R. et al., 1994. COMPTEL observations of galactic ^{26}Al emission. A&A 298, 445.

Hoyle, F., 1946. The synthesis of the elements from hydrogen. MNRAS 106, 343–383.

Hoyle, F., 1954. Synthesis of the elements from carbon to nickel. ApJ (Suppl. 1), 121–146.

Lee, T., Papanastassiou, D.A., Wasserburg, G.J., 1977. ^{26}Al: fossil or fuel. ApJ 211, L107.

Mahoney, W.A., Ling, J.C., Wheaton, W.A., Jacobson, A.S., 1984. HEAO 3 discovery of ^{26}Al in the interstellar medium. ApJ 286, 578–585.

Ramaty, R., Lingenfelter, R.E., 1977. ^{26}Al: a galactic source of gamma-ray-line emission. ApJ 213, L5–L7.

Savina, M.R., Davis, A.M., Tripa, C.E., Pellin, M.J., Gallino, R., Lewis, R.S., Amari, S., 2004. Extinct technetium in silicon carbide stardust grains: implications for stellar nucleosynthesis. Science 303, 649–652.

The, L.-S., El Eid, M., Meyer, B.S., 2000. A new study of s-process nucleosynthesis in massive stars. ApJ 533, 998–1015.

The, L.-S., Clayton, D.D., Diehl, R., Hartmann, D.H., Iyudin, A.F., Leising, M.D., Meyer, B.S., Motizuki, Y., Schönfelder, V., 2006. Are ^{44}Ti-producing supernovae exceptional? A&A 450, 1037–1050.

Timmes, F.X., Clayton, D.D., 1996. Galactic evolution of silicon isotopes: application to presolar SiC grains from meteorites. ApJ 472, 723–741.

Woosley, S.E., Arnett, W.D., Clayton, D.D., 1973. Explosive burning of oxygen and silicon. ApJ (Suppl. 26), 231–312.

[1] In several conversations with Hoyle about the alpha process, he did not lament inadequate proofreading; but on more than one discussion of this topic he responded simply, "It was my fault", without explanation. I personally knew him to be a lax proofreader from papers we coauthored. He was more interested in the creative ideas than in proofreading them. Hoyle never said one word to me that was critical of any coauthors, but characteristically took blame onto himself for inadequacies of B^2FH.