Arch. Hist. Exact Sci. (2010) 64:721–751
DOI 10.1007/s00407-010-0068-8

An anthropic myth: Fred Hoyle's carbon-12 resonance level

Helge Kragh

Received: 7 June 2010 / Published online: 1 July 2010

Abstract The case of Fred Hoyle's prediction of a resonance state in carbon-12, unknown in 1953 when it was predicted, is often mentioned as an example of anthropic prediction. However, an investigation of the historical circumstances of the prediction and its subsequent experimental confirmation shows that Hoyle and his contemporaries did not associate the level in the carbon nucleus with life. Only in the 1980s, after the emergence of the anthropic principle, did it become common to see Hoyle's prediction as anthropically significant. At about the same time mythical accounts of the prediction and its history began to abound. Not only has the anthropic myth no basis in historical fact, it is also doubtful if the excited levels in carbon-12 and other atomic nuclei can be used as an argument for the predictive power of the anthropic principle.

1 Introduction

In the early days of 1953 the British astrophysicist and cosmologist Fred Hoyle famously predicted the existence of an excited state in the carbon-12 atomic nucleus, arguing that such a state was necessary for the production of appreciable amounts of carbon in the stars. The prediction was quickly confirmed in laboratory experiments and is today recognized as a breakthrough in the understanding of stellar nucleogenesis. When the Royal Swedish Academy of Sciences awarded the prestigious Crafoord Prize of 1997 to Hoyle for his pioneering contributions to astrophysics, it mentioned specifically his prediction of the carbon energy level as "perhaps his most important

Communicated by Roger Stuewer.

H. Kragh (✉)
Department of Science Studies, University of Aarhus, Building 1110, 8000 Aarhus, Denmark
e-mail: helge.kragh@ivs.au.dk

single contribution within the field."[1] The prize for 1997, which apart from the honor included half a million US dollars, was shared between Hoyle and the American astrophysicist Edwin Salpeter whose study on the "triple alpha process" in the 1950s was closely connected with Hoyle's.

In spite of its importance, Hoyle's prediction has never been investigated from a historical perspective, nor has its relationship to the later anthropic principle been examined in any depth. My primary aim in this article is to offer a critical historical analysis of how Hoyle arrived at his prediction and the role it played in astrophysics in the 1950s. I am particularly concerned with the alleged anthropic nature of the prediction and how Hoyle himself looked upon the question. Is it really true, as was asserted by theoretical physicist Leonard Susskind, that Hoyle was able to predict the synthesis of carbon "just from the fact that we are here"?[2] Apart from examining the anthropic claim, I describe the state of research on stellar nucleosynthesis in the years before and after Hoyle's prediction, paying particular attention to the experimental work done by William A. Fowler and his group of nuclear physicists at the Kellogg Radiation Laboratory.

While my article is basically a contribution to the history of astrophysics, it also addresses issues of a more general nature related to anthropic predictions. This subject is of considerable philosophical interest and has several times been discussed within the context of philosophy of science.[3] I shall argue that the proper philosophical significance of the case of the carbon-12 resonance can only be appreciated if its complex history is taken into account. In the last section I discuss from a more general perspective the possible anthropic significance of Hoyle's remarkable prediction.

2 The anthropic claim

The anthropic principle was first explicitly formulated by the Australian-born astrophysicist Brandon Carter, a former student of Dennis Sciama, in a lecture at Cracow in 1973. According to Carter, the essence of what he called the weak anthropic principle (WAP) was that "we must be prepared to take account of the fact that our location in the universe is necessarily privileged to the extent of being compatible with our existence as observers."[4] Ever since Carter's announcement of the anthropic principle it has been discussed whether this controversial principle (in one of its several versions) belongs to science or philosophy. It is generally agreed that the anthropic principle, to be of any scientific value, must result in predictions of more or less the same kind as known from ordinary scientific theories, preferably in precise predictions of phenomena that are not known to exist at the time of the prediction. Among the very few anthropic predictions—and possibly the only one—that belong to this category

1 http://www.crafoordprize.se.

2 Susskind (2006, p. 182).

3 See, e.g., Leslie (1994), Klee (2002), Walker and Ćirković (2003), and Mosterin (2004).

4 Carter (1974, p. 293); reprinted in Leslie (1990, pp. 125–133). For the history of the anthropic principle, see Kragh (2010).

is Fred Hoyle's prediction in 1953 of a definite resonance state in carbon-12, the one that most frequently has appeared in the anthropic literature.

To summarize this well-known case, in 1953 Hoyle realized that to make enough carbon inside the stars, there had to exist a resonance state of the carbon-12 nucleus at 7.68 MeV above the ground level. At the time this state was not known experimentally. Although Hoyle's theoretical arguments were at first met with some skepticism, experiments made at the California Institute of Technology (Caltech) soon confirmed the predicted resonance. Hoyle had apparently shown that an unknown property of the carbon nucleus, a manifestation of the precise strength of the nuclear and electromagnetic forces, follows from the undeniable existence of carbon-based life. We exist, consequently there must be a 7.68 MeV carbon-12 resonance! The story of how Hoyle made his famous and alleged anthropic prediction has been told numerous times, in many cases as evidence of the predictive power of anthropic arguments. "Hoyle was rigorously applying what would later become known as the anthropic principle," one can read.[5] "This was the first and only time that a scientist had made a prediction using the anthropic principle and had been proved right." Statements like this abound, both in published sources and, not least, on the internet.

To my knowledge, the first time that the case of the carbon resonance appeared explicitly in an anthropic context was in an influential article by Bernard Carr and Martin Rees of 1979, in which the two scientists discussed and summarized all the arguments for the anthropic principle known at the time. However, apparently Carr and Rees did not consider the 7.65 MeV resonance level a proper case of anthropic prediction, for they concluded that the anthropic principle "is entirely post hoc: it has not yet been used to predict any feature of the Universe."[6] Ten years later, Rees, now in a popular book written jointly with the astrophysicist and science writer John Gribbin, gave a much more detailed account of the case and its anthropic nature. As the two authors noted, most anthropic arguments are made with the benefit of hindsight, the predictions being really *postdictions*. "But Hoyle's prediction is different, in a class of its own," they said, "It is a genuine scientific prediction, tested and confirmed by *subsequent* experiments."[7] They elaborated:

> Hoyle said, in effect, "since we exist, then carbon must have an energy level at 7.6 MeV." Then the experiments were carried out and the energy level was measured. As far as we know, this is the only genuine anthropic principle prediction; all the rest are "predictions" that *might* have been made in advance of the observations, if anyone had the genius to make them, but that were never in fact made in that way. ... There is no better evidence to support the argument that the Universe has been designed for our benefit—tailor-made for man.[8]

[5] Singh (2004, p. 395).

[6] Carr and Rees (1979, p. 612). The Russian physicist Iosif Rozental included Hoyle's resonance as an example of anthropic fine-tuning in an article of 1980 in *Soviet Physics Uspekhi*; see Rozental (1980, English translation of 1981).

[7] Gribbin and Rees (1989, p. 247).

[8] Ibid.

We find what is basically the same argument, spelled out in considerable detail, in *The Anthropic Cosmological Principle*, the encyclopedic and influential study published by John Barrow and Frank Tipler in 1986. The two authors referred to "Hoyle's anthropic prediction" not only in connection with the carbon resonance but also with regard to the energy levels of oxygen-16: "Hoyle realized that this remarkable chain of coincidences—the unusual stability of beryllium, the existence of an advantageous resonance level in C^{12} and the non-existence of a disadvantageous level in O^{16}—were necessary, and remarkably fine-tuned, conditions for our own existence and indeed the existence of any carbon-based life in the Universe."[9] Using the past tense, readers of the book inevitably get the impression that Hoyle's anthropic insight went back to his study in 1952–1954, whereas in reality, as we shall see, it dates from a much later period. Barrow was among the first scientists to explicitly describe Hoyle's prediction as anthropic, such as he did in an article of 1981, although at that time he did not claim that the prediction was actually anthropically motivated.[10]

A good story told many times easily becomes self-perpetuating. It tends to live a life of its own; there are many examples in the history of science, Hoyle's anthropic prediction being one of them. In an early bibliography of anthropic literature, the philosopher Yuri Balashov repeated the myth: "In 1953 Hoyle made an anthropic prediction of an excited state—'level of life'—of ^{12}C at 7.6 MeV needed for carbon production in the interior of stars."[11] The claim reappears in the more recent literature, both scientific and popular, in much the same form as when it was first told in the 1980s. Thus, to the prominent theoretical cosmologist Andrei Linde, "the existence and properties of this [carbon] resonance was one of the first successful predictions based on the anthropic principle."[12] Also Brandon Carter, the inventor of the anthropic principle, came to believe that the prediction qualifies as anthropic. In 2006 he said: "A prototype example of the application of this 'strong' kind of anthropic reasoning was provided by Fred Hoyle's observation that the triple alpha process . . . is extremely sensitive to the values of the coupling constants governing the relevant thermonuclear reactions in large main sequence stars."[13]

What may be called the "anthropic myth" exists in two versions. One of the versions, illustrated by the quotations from Linde and Carter, reconstructs Hoyle's argument as *de facto* anthropic, without making a historical claim. According to the other version, exemplified by the quotations from Balashov and from Barrow and Tipler, Hoyle was originally motivated by considerations of life in the universe to make the prediction. The cosmologist Jayant Narlikar, a close collaborator of Hoyle, writes about Hoyle's motivation for making the prediction of the resonance level that life would be impossible without carbon and oxygen. "Thus the fact that we human beings are around to

[9] Barrow and Tipler (1986, p. 253).

[10] Barrow (1981, p. 414).

[11] Balashov (1991, p. 1072).

[12] Linde (2007, p. 144).

[13] Carter (2006, p. 176). The strong anthropic principle (SAP) exists in several versions, but can be boiled down to the statement that the universe must have those properties that allow (intelligent) life to develop within it at some stage in its history. The weak form of the anthropic principle (WAP) is the almost (but only almost) trivial statement that the observed properties of the universe must be consistent with observers.

observe the universe makes it imperative that the route to making carbon and oxygen must be open!"[14]

As one might expect, the story is an element in many of the obituaries, biographies, and commemorative articles which have appeared after Hoyle's death in 2001. "Hoyle had anticipated the anthropic principle by arguing that because we are here, this C^{12} excited state must exist," says one of the obituaries written by a distinguished astrophysicist.[15] On the occasion of the fifty-year's anniversary of the 1953 prediction, *The Guardian* included an article on how Hoyle originally presented his deduction of a 7.65 MeV state to the American nuclear experimentalist and later Nobel laureate William A. Fowler. "The state had to exist, reasoned Hoyle, because life existed and life was based on carbon." The skeptical Fowler found it outrageous: "What compounded Fowler's amazement was the manner of Hoyle's prediction. He had predicted the 7.65 MeV energy state of carbon-12 using an anthropic argument: it had to exist because, if it didn't, neither could human beings. To Fowler, such flaky logic smacked of religion rather than science. To this day, Hoyle is the only person to have made a successful prediction from an anthropic argument in advance of an experiment."[16]

Many more examples could be provided, but the ones quoted will suffice to illustrate the widespread belief or myth that Hoyle's prediction of the early 1950s was an early example of *bona fide* anthropic reasoning, or an anticipation of the anthropic principle *avant le mot*. The problem with the belief is not the predictive nature of Hoyle's argument, but its supposed anthropic nature.

3 The triple alpha process

From a historical point of view, the problem of explaining the formation of chemical elements is closely related to the problem of accounting for energy production in the stars.[17] While the latter problem goes back to Arthur Eddington's seminal studies of the 1920s, culminating in his classical study, *The Internal Constitution of the Stars* of 1926, the first one was pioneered a decade later by George Gamow, Harold Walke, Carl Friedrich von Weizsäcker, and a few other physicists. In a pathbreaking study of 1939, Hans A. Bethe developed a detailed quantum-mechanical theory of the nuclear processes fueling main sequence stars such as the Sun. According to Bethe, the key process was a cyclic reaction where four protons, interacting catalytically with carbon and nitrogen nuclei, were turned into an alpha particle.[18] He also briefly considered red giant stars, but only to conclude that the cyclic reaction did not work for these.

In Bethe's theory of the carbon–nitrogen (CN) cycle, carbon played a crucial role as a catalytic agent, but Bethe merely assumed the existence of carbon rather than accounting for its genesis. Although his theory was mainly concerned with energy

[14] Narlikar (1999, p. 102).

[15] Clayton (2001, p. 1570) and also in Clayton (2007a,b). For the biographies, see section 6.

[16] Chown (2003), online version, and similarly in Chown (1999, p. 176).

[17] For the historical development of nuclear astrophysics and stellar evolution from about 1920 to 1950, see Kragh (1996, pp. 81–101), Tassoul and Tassoul (2004, pp. 100–166), and Hufbauer (2006).

[18] Bethe (1939); partially reprinted in Lang and Gingerich (1979, pp. 320–338).

production, and not with nucleosynthesis, he did discuss what he called triple collisions of alpha particles, including the direct formation of carbon-12 by the collision of three alpha particles, that is, $3\ ^{4}\mathrm{He} \rightarrow\ ^{12}\mathrm{C}$. However, he found that the yield of carbon would be negligible unless the temperature was $T \sim 10^9$ K, much higher than the 2×10^7 K of the interior of the Sun and similar stars. Bethe concluded that "there is no way in which nuclei heavier than helium can be produced permanently in the interior of stars under present conditions."[19] Yet, somehow carbon, oxygen, and the other elements had come into existence. How?

Bethe's study relied intimately on experimentally determined cross sections for nuclear reactions, and it demonstrated to nuclear physicists that their work might be valuable, indeed crucial, to the physics of the stars. Physicists at Caltech's Kellogg Radiation Laboratory, built in 1931 with funds supplied by the Detroit cornflakes magnate Will Keith Kellogg, were among the first to enter the new field of nuclear astrophysics.[20] Under the leadership of Charles Lauritsen, they were already studying the reaction between carbon-12 and protons—meaning $^{12}\mathrm{C}(\mathrm{p}, \gamma)^{13}\mathrm{N}$—the first process in the CN cycle, although at first without thinking of its astrophysical relevance. Bethe's study on the CN cycle came as a revelation, as recalled by Fowler, who had joined Lauritsen's group in 1933 while still a graduate student: "Bethe's paper told us that we were studying in the laboratory processes which are occurring in the sun and other stars. It made a lasting impression on us."[21] It was only after World War II, however, that Fowler and other Kellogg physicists began to focus on low-energy nuclear astrophysics, first on energy-producing processes and later on stellar nucleosynthesis. Detailed studies of the rate of the CN cycle led Fowler and his collaborators to conclude that the CN cycle did not power the Sun, such as Bethe had argued. The dominant process in the Sun, they concluded, was the proton–proton chain that had been presented by Bethe and Charles Critchfield a little earlier than Bethe's study on the CN cycle.[22]

The Kellogg Laboratory had the advantage that it was part of an institution, Caltech, which at the time became strongly engaged in astronomy and astrophysics. The turn to nuclear astrophysics was supported by Ira Bowen, a Caltech physics professor who had done work on cosmic rays and astrospectroscopy and in 1946 was appointed director of the Mount Wilson Observatory. When the astronomer Jesse Greenstein in 1948 came to Caltech to build up an astronomy graduate program it further helped to give the laboratory a clearer orientation toward experimental astrophysics, at the time the only institution of its kind. One of the Fowler's first astrophysical studies, a review dealing with stellar nucleosynthesis, was done in collaboration with Greenstein.[23]

While the production of heavier elements was not part of Bethe's astrophysical study, it was of crucial importance to the cosmological research program initiated by

[19] Bethe (1939, p. 446). The "present conditions" Bethe referred to were the density and temperature in the interior of main-sequence stars, about $\rho = 30\,\mathrm{g\,cm}^{-3}$ and $T = 2 \times 10^7$ K.

[20] The Kellogg Laboratory was initially established to treat cancer patients by means of a high-voltage X-ray apparatus. For its history, see Greenberg and Goodstein (1983) and Holbrow (1987).

[21] Fowler (1984, p. 923). See also the interview with Fowler in Greenberg (2005).

[22] Fowler (1954); Bethe and Critchfield (1938).

[23] Fowler and Greenstein (1956).

George Gamow in 1946 and developed in collaboration with Ralph Alpher and Robert Herman in particular. The essence of the Gamow approach to cosmology was the big bang assumption of an early, hot, and compact universe in which the elements had been formed by neutron capture and other nuclear processes within the first few hours of the cosmic expansion. However, it turned out that only the formation of the lightest elements, the hydrogen and helium isotopes, could be explained in this way. The problem, known as the "mass-gap problem," was the nonexistence of nuclei of atomic weights 5 and 8 which were needed as "bridges" between helium and carbon. Even before the war, Kellogg physicists Hans Staub and William Stephens had confirmed that there was no stable helium nucleus at mass 5.[24] The same was later shown to be true for lithium-5, the other candidate nucleus at mass 5. Moreover, it was also assumed that the same was the case for mass 8, the lifetime of beryllium-8 being only about 10^{-16} s.[25] The instability of the three nuclei was convincingly argued by Bethe in his 1939 article on the CN cycle.

Gamow and his associates tried hard to solve or circumvent the mass-gap problem, but their efforts met with no success. The problem was studied in detail by Enrico Fermi and his Chicago colleague Anthony Turkevich, but after many ingenious suggestions they, too, were "left with the sad conclusion that this theory [Gamow's] is incapable of explaining the way in which the elements have been formed."[26] In regard of Hoyle's later prediction it is of some interest to note that at one stage Fermi and Turkevich considered the process

$$^{3}\mathrm{H} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Li} + \gamma.$$

They found that "a resonance would have to be at about 400 keV or closer in order to convert any appreciable amount of the material into Li^7."[27] Unfortunately no such resonance had been found experimentally and for this reason the attempt to bridge the gap at mass 5 was abandoned. Another suggestion, made by Turkevich and based on an unpublished idea of Eugene Wigner, was the exothermic process

$$^{3}\mathrm{H} + {}^{10}\mathrm{C} \rightarrow {}^{6}\mathrm{Li} + {}^{7}\mathrm{Be}.$$

However, the hypothetical reaction fared no better than other suggestions.

By the early 1950s it thus seemed impossible that carbon and the other heavy elements of atomic number $Z > 4$ could have been produced cosmologically in the early universe, and it seemed equally impossible that they could be produced in ordinary stars. In a study of 1951 the Estonian-Irish astronomer Ernst Öpik suggested that what

24 Staub and Stephens (1939).

25 On beryllium-8, see Wheeler (1940). Experiments of 1937 indicated that the disintegration energy of beryllium-8 into two alpha particles was in the range 40–120 keV (Kirchner et al. 1937).

26 Fermi (1949, p. 720). On the mass gap problem in Gamow's big bang theory of the universe, see Kragh (1996, pp. 128–132). Although the study of Fermi and Turkevich was never published, it was known from summary accounts given by Gamow and his coworkers, see in particular Alpher and Herman (1950, pp. 193–202).

27 Alpher and Herman (1950, p. 196).

was not possible in ordinary main-sequence stars might be realized in red-giant stars.[28] In the late phase of such a star the contracting core reaches a temperature of about 4×10^8 K, and Öpik argued that at this temperature it would be possible for nearly all helium to convert into carbon by a triple alpha process, thus circumventing the mass-gap problem. However, Öpik's article had almost no influence and was initially unknown even to astrophysicists working in the same research area.

One of those astrophysicists was Edwin Salpeter, a young Austrian-born theorist at Cornell University who had worked with Bethe on problems of quantum mechanics and quantum electrodynamics. In the summer of 1951 Salpeter was invited to spend some time with Fowler and his group at the Kellogg Radiation Laboratory. In one of his first studies on nuclear astrophysics Salpeter argued, much like Öpik but in greater detail, that in red-giant stars at $T > 10^8$ K three alpha particles would fuse into carbon.[29] In spite of the instability of beryllium-8, a small amount of this isotope will be built up, just sufficient to permit the further addition of an alpha particle. Salpeter's process would occur in the two reactions

$$
\begin{aligned}
&{}^4\mathrm{He} + {}^4\mathrm{He} + \mathrm{Q}_1 \rightarrow {}^8\mathrm{Be} + \gamma \quad (\mathrm{Q}_1 = 95\,\mathrm{keV}) \\
&{}^4\mathrm{He} + {}^8\mathrm{Be} \rightarrow {}^{12}\mathrm{C}^* \rightarrow {}^{12}\mathrm{C} + \gamma + \mathrm{Q}_2 \quad (\mathrm{Q}_2 = 7.4\,\mathrm{MeV})\,.
\end{aligned}
$$

For the rate of energy production ε of the triple alpha process, as expressed in units of $\mathrm{erg\,g^{-1}\,s^{-1}}$, he found for temperatures $T \sim 2 \times 10^8$ K

$$
\varepsilon = 10^3 \left(\frac{\rho}{2.5 \times 10^4}\right)^2 \left(\frac{T}{2 \times 10^8 K}\right)^{18} Y^3,
$$

where ρ is the density in $\mathrm{g\,cm^{-3}}$ and Y is the concentration by weight of helium. Salpeter first calculated these results in July 1951, during his stay at Caltech.[30]

Measurements made at Los Alamos and the Kellogg Radiation Laboratory a few years earlier had confirmed that beryllium-8, although unstable, is only so by a slight amount, namely about 95 keV. The Los Alamos physicist Arthur Hemmendinger obtained 103 ± 10 keV for the disintegration energy of beryllium-8 into two alpha particles, while Fowler and his collaborators reported 89 ± 5 keV.[31] Salpeter reasoned that the ground state of the nucleus provided a resonance level at a low excitation energy for a pair of alpha particles. Thus, at the high temperature in a red giant, there will be a fraction of the alpha particles that have thermal energies high enough to form beryllium-8 nuclei. Although these have a lifetime of only 10^{-16} s, at a temperature in the vicinity of 2×10^8 K beryllium-8 will be continuously present. According to Salpeter's estimate, the result would be an equilibrium ratio of beryllium-8 to helium-4 of the order of 10^{-10}. Under these conditions beryllium-8 could absorb another

[28] Öpik (1951).

[29] Salpeter (1952), submitted 2 October 1951 and reproduced in Lang and Gingerich (1979, pp. 349–352). See also the recollections in Salpeter (2002, especially pp. 8–10). The Salpeter triple alpha process was first reported in the 23 February 1952 issue of *Nature* (Bondi and Salpeter 1952).

[30] Salpeter (2008).

[31] Hemmendinger (1949) and Tollestrup et al. (1949).

alpha particle and form carbon-12. Salpeter also considered (as had Öpik) the further formation of elements of $Z > 6$, such as

$$^{12}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O} + \gamma + \mathrm{Q}_1 \quad (\mathrm{Q}_1 = 7.1\,\mathrm{MeV})$$
$$^{16}\mathrm{O} + {}^{4}\mathrm{He} \rightarrow {}^{20}\mathrm{Ne} + \gamma + \mathrm{Q}_2 \quad (\mathrm{Q}_2 = 4.7\,\mathrm{MeV}).$$

Taking into account the resonance effects due to the ground state of beryllium-8, Salpeter's rate equation indicated a rate for helium burning considerably greater than the one calculated by Öpik (which he did not know about at the time). In his brief article published in the *Astrophysical Journal* in 1952, Salpeter noted that the calculated rate might depend on the position of resonance levels in carbon-12.[32] If an appropriate resonance level existed, the production rate could be larger than the estimated one by a factor of 1,000 or more. But he did not follow up on the remark. Fifty years later Salpeter reflected that "I did not have the chutzpah (or guts) to do anything about it." The calculation made in 1951, he said (evidently with hindsight), "would lead to most of the helium being converted to oxygen and neon instead of carbon, but I just did not have the guts to think of resonance levels that had not been found yet!"[33]

4 Prediction and confirmation

Fred Hoyle had the chutzpah that Salpeter admittedly lacked. Contrary to Salpeter, Hoyle had for long been interested in nuclear astrophysics and the processes in the interior of the stars that generated the chemical elements. In an important article of 1946 he examined the formation of heavier elements up to about the middle of the periodic system, concluding that the most abundant of these elements would be grouped about iron.[34] As to the lighter elements, he assumed that carbon-12 was somehow formed by helium nuclei, but without considering the mechanism. In this long and complex article he did not deal with the details of the nuclear reactions but merely established the general framework for element formation.

In the fall of 1952 Hoyle was invited to spend the first 3 months of 1953 at Caltech. Having arrived in Pasadena a few days before New Year, he decided to follow up on Salpeter's study by taking a fresh look at the triple alpha process generating carbon. One reason for his dissatisfaction with Salpeter's calculations may have been his conviction that helium burning in red giants should start at temperatures just above 10^8 K rather than at 2×10^8 K as assumed by Salpeter. Greatly interested in all aspects of stellar evolution, Hoyle was aware of a recent study by Allan Sandage and Martin Schwarzschild on stellar models with gravitationally contracting cores. According to one of the models by Sandage and Schwarzschild, the central temperature might be as low as 1.1×10^8 K, which they admitted was "rather lower than the temperature

[32] Salpeter (1952).

[33] Salpeter (2002, p. 9). "Chutzpah" is a Jewish-English word meaning "audacity" or "nerve."

[34] Hoyle (1946). For accounts of Hoyle's study on stellar nucleosynthesis, see Arnett (2005) and Mitton (2005, pp. 197–222).

needed for helium burning (2×10^8 K) as derived by Salpeter."[35] While Sandage and Schwarzschild did not consider the discrepancy to be serious, Hoyle saw it as a problem for Salpeter's reaction-rate equation. Much later, Hoyle recalled his reconsideration of the triple alpha process:

> Salpeter's publication of the 3α process freed me to take a fresh look at the carbon production problem. I found difficulty in generating enough carbon, because the carbon kept slipping away into oxygen as it was produced. A theoretically possible way around this difficulty was greatly to speed-up the carbon synthesis by a rather precisely tuned resonance which would need to be about 7.65 MeV [originally 7.68 MeV] above ground-level in the ^{12}C nucleus.[36]

In another recollection of the events from his fruitful stay at Caltech, Hoyle said:

> It was in early January, 1953 that I decided to add $^8\text{Be}(\alpha, \gamma)^{12}\text{C}$ to the 3α process, finding that it appeared to scour out the carbon as fast as it was produced. Bad luck for poor old Ed I thought to myself, through a happy hour or two before common sense reasserted itself. There just had to be some way of synthesizing ^{12}C. Nothing was better than 3α and so 3α had to go a lot faster than it had been calculated to do. To go faster, a resonant state at about 7.65 MeV above the ground state would be needed. The trouble was that there appeared to be no such state, which was the problem I had on my mind as I walked into Willy's [Fowler's] office in the Kellogg Laboratory.[37]

That is, Hoyle realized that to get an appreciable fraction of the original helium transformed into carbon-12, the $^8\text{Be}(\alpha, \gamma)^{12}\text{C}$ process had to proceed resonantly at an energy level of about 7.68 MeV or 0.31 MeV above the sum of the masses of beryllium-8 and helium-4. The predicted state was about 3.2 MeV above the first excited state of carbon-12, which was known experimentally (Fig. 1). "Assuming ... that the $\text{Be}^8 + \alpha$ reaction through this level is not forbidden by strict selection rules," he wrote in an article of 1954, "the resonance contribution from it quite overwhelms not only the nonresonance yield but also the resonance contributions from other levels."[38]

With the new hypothesized resonance the carbon yield would increase by a factor of about 10^7 compared to that of the Salpeter process. Moreover, Hoyle also realized that the enormous enhancement of the triple alpha process by means of the resonance was not enough to secure a sufficient net yield of carbon-12. Because, if the produced carbon-12 were consumed by other reactions, and especially by the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ process, nothing would have been gained. By comparing the reaction rates of the two processes he found that the latter must occur through a known nonresonant level at 7.10 MeV above the ground state of oxygen-16, slightly less than what corresponds

[35] Sandage and Schwarzschild (1952, p. 475); reprinted in Lang and Gingerich (1979, pp. 353–363). See also Hoyle and Schwarzschild (1955, especially p. 31). The two articles are analyzed in Cenadelli (2010), according to whom the Hoyle–Schwarzschild article is a "landmark paper."

[36] Hoyle (1986, p. 449).

[37] Hoyle (1982a, pp. 2–3). "Poor old Ed" was Hoyle's junior by 9 years.

[38] Hoyle (1954, p. 130).

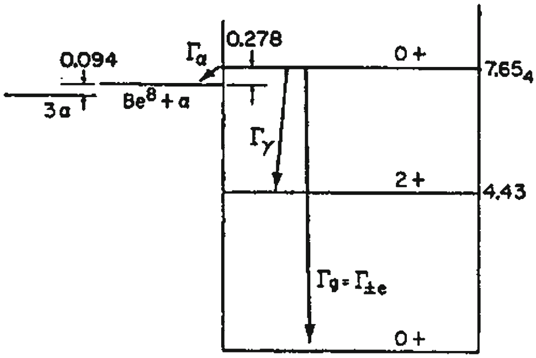

Fig. 1 Some of the energy levels in carbon-12, compared with the energies of 3α and ($Be^8 + \alpha$). *Source* Salpeter (1957, p. 517)

to the combined masses of carbon-12 and the alpha particle. Because the 7.10 MeV level is just below ($^{12}C + \alpha$) = 7.16 MeV, resonance cannot occur.

In this way Hoyle was able to explain how most of the carbon produced in the core of a giant star will still be present when the star explodes as a supernova and spreads its material into interstellar space. In his account of the theory, as first presented in an article in *Astrophysical Journal* of 1954, Hoyle concluded that the theory was able to reproduce roughly the abundance ratios between carbon-12, oxygen-16, and neon-20, but only if there existed a carbon resonance level at about 7.7 MeV.[39] For the ratios he deduced

$$^{12}C : {}^{16}O \sim 1{:}3 \quad \text{and} \quad {}^{16}O : {}^{20}Ne \sim 1{:}1,$$

in good agreement with astrospectroscopic estimates. Thus, with Hoyle's new insight the steps in the triple alpha reaction could be written as

$$\begin{aligned} &^{4}He + {}^{4}He + Q_1 \rightarrow {}^{8}Be + \gamma \\ &^{4}He + {}^{8}Be + Q_2 \rightarrow {}^{12}C^{*} \\ &^{12}C^{*} \rightarrow {}^{12}C + 2\gamma + Q_3 \end{aligned}$$

where $Q_1 = 95$ keV, $Q_2 = 0.31$ MeV and $Q_3 = 7.68$ MeV. The net result was

$$^{4}He + {}^{4}He + {}^{4}He \rightarrow {}^{12}C + 2\gamma + 7.28\,\text{MeV}.$$

Whereas Hoyle did not calculate a reaction rate for the revised triple alpha process, other physicists, following up on his idea, did. Taking into regard the Hoyle resonance they found a rate equation of the same form as the one Salpeter had reported in 1952, but with a much larger yield. Moreover, the energy generation turned out to

39 Hoyle (1954, p. 134). Although today recognized as a pioneering contribution to the understanding of stellar nucleosynthesis, Hoyle's article of 1954 was not well known and only cited by few scientists. For the reasons for the lack of citations to the article, see Clayton (2007a,b) and Burbidge (2008).

be extremely sensitive to the temperature. For a temperature at about 1.4×10^8 K, the general form of the rate equation can be written as

$$\varepsilon = 10^{-8} \rho^2 Y^3 \left(\frac{T}{10^8} \right)^{30},$$

as given in Martin Schwarzschild's pioneering textbook, *Structure and Evolution of the Stars*.[40]

Hoyle did not rush to announce his prediction, which only became known to the community of physicists more than half a year after it had been confirmed experimentally. His announcement took place at a meeting of the American Physical Society in Albuquerque in early September 1953, five months after Hoyle had left Caltech for a stay at Princeton University. In its brief abstract Hoyle and his three coauthors said that the observed cosmic abundance ratio of He:C:O could be reproduced "if the reaction $Be^8(\alpha, \gamma)C^{12}$ has a resonance state near 0.31 MeV, corresponding to a level at 7.68 MeV in C^{12}."[41] This first presentation was actually the study of the Kellogg experimentalists and not Hoyle, who at the time had left Pasadena and was back at the University of Cambridge. According to the recollections of Ward Whaling, "We wrote to him [Hoyle] and said, 'We're going to publish a paper and we'd like you to put your name on it, too.' ... And he acceded, since the experiment—he didn't get in and turn and twist the knobs and read the counters, but it was his idea, his concept, that led us to do it in the first place."[42] A fuller account of the reactions only appeared in Hoyle's more extensive article in the *Astrophysical Journal* of 1954, in which the predicted excited state was not given much emphasis. In fact, Hoyle did not mention the prediction at all, merely citing the experimental confirmation of Whaling and his group.

Since Hoyle had his office in the Kellogg Laboratory it was natural for him to approach Fowler and the other Kellogg experimentalists with regard to having his prediction confirmed. The encounter between the British theorist and the American experimentalists has been told in various versions. In one of the versions Fowler recalled:

> I was very skeptical that this steady state cosmologist, this theorist, should ask questions about the carbon-12 nucleus. ... Here was this funny little man who thought that we should stop all this important work that we were doing otherwise and look for this [resonance] state, and we gave him the brushoff. Get away from us, young fellow, you bother us.[43]

40 Schwarzschild (1958, p. 85).

41 Hoyle et al. (1953).

42 Interview with Ward Whaling by Shelley Erwin, April–May 1999, California Institute of Technology Archives. Available online at http://resolver.caltech.edu/CaltechOH:OH_Whaling_W. See also Spear (2002).

43 Interview with W. Fowler by Charles Weiner, American Institute of Physics, February 1973, as quoted in Kragh (1996, p. 299). In his Nobel Lecture of 1983 (Fowler 1984), and also in the interview with John Greenberg of 1984 (Greenberg 2005), Fowler gave a less dramatic account of the meeting between Hoyle and the Kellogg physicists.

Fowler's recollection may be more colorful than accurate. In any case, it does not agree with the memory of Hoyle, according to whom his request to Fowler merely resulted in "a long technical discussion of whether the experimental methods used thus far might have missed the state I was looking for."[44] The Kellogg nuclear physicist Charles Barnes recalled the meeting in Fowler's office as follows:

> As Fred presented his ideas, it was clear that the audience was visibly skeptical. Even Willy seemed to be somewhat skeptical, but I don't recall that he raised any serious objections to the ideas, whatever he thought about them. Toward the end of the meeting, I recall saying that we could and should certainly check whether there really was an excited state in ^{12}C near the ^{8}Be plus alpha threshold, as Fred was proposing, and that Ward [Whaling] and his group . . . were in a particularly good position to do the measurement.[45]

Whatever the details, Fowler and his team quickly took an interest in what Hoyle told them and prepared looking for the missing resonance. One reason may have been that the prediction of a resonance level at about 7.7 MeV, although unconfirmed at the time, was not completely unexpected.

Thus, as early as 1940, two physicists at Cornell University had reported an energy level in carbon-12 at 7.62 MeV based on measurements of the range of alpha particles from the reaction ^{14}N(d, α)^{12}C, where d denotes a deuteron.[46] However, later and more precise measurements of the same deuteron-nitrogen reaction, made by R. Malm and W. Buechner at the Massachusetts Institute of Technology, failed to confirm a level at about this energy.[47] On the other hand, some studies of nuclear processes seemed to provide evidence for a level in the area 7.0–7.5 MeV, which was included as a possibility in some of the level diagrams published by the Kellogg Radiation Laboratory in the early 1950s (Fig. 2).[48] What matters is that by 1952 there was conflicting evidence in regard to the question of a carbon-12 state in the vicinity of 7.5 MeV, not far from the state that Hoyle needed. Hoyle was probably aware of the possibility of such a resonance, which may have stimulated his decision to examine the triple alpha process more closely. Thus, it is not quite true that the 7.68 MeV excited state was "contrary to all the then-known evidence," such as the standard story has it.[49]

It has been suggested that Hoyle did not really predict a new energy level, but rather "predicted that the newly expunged level would be real," as stated by David Arnett,

[44] Hoyle (1994, p. 264).

[45] Communication of December 2001 to Ray Spear, an Australian nuclear physicist, as quoted in Spear (2002, p. 38).

[46] Holloway and Moore (1940).

[47] Malm and Buechner (1951).

[48] Hornyak et al. (1950, p. 325), Britten (1952), and Ajzenberg and Lauritsen (1952, p. 355). For more references to pre-1953 studies on the energy levels of carbon-12, see Cook et al. (1957).

[49] Scerri (2007, p. 257). Eric Scerri, a philosopher and historian of the chemical sciences, is one more author who conveys the anthropic myth: "Hoyle had reasoned that the resonant state of carbon had to exist since beings like us are made largely by carbon and are able to pose the questions as to the formation of the element carbon" (p. 323).

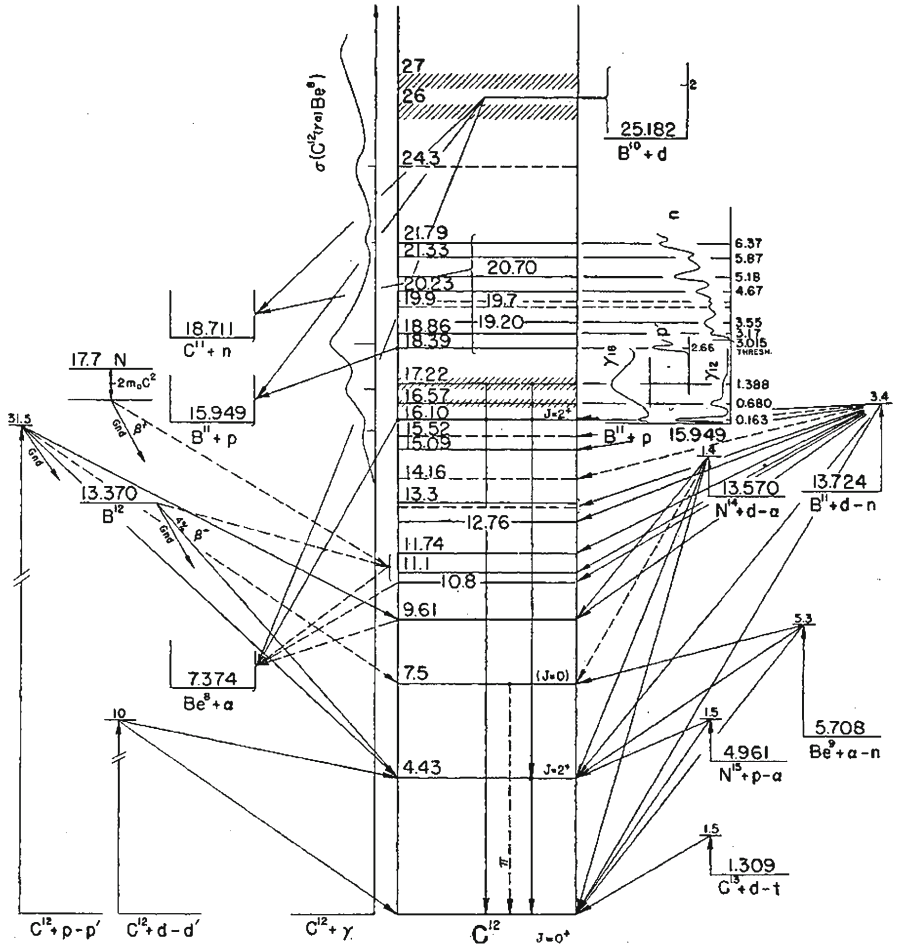

Fig. 2 Energy levels of carbon-12. Notice the level at 7.5 MeV above the ground state. *Source* Ajzenberg and Lauritsen (1952, p. 355)

an American astrophysicist.[50] Yet, even though there was unconfirmed evidence of one or more resonances in the range 7.0–7.5 MeV, Hoyle's prediction did not depend on this evidence. Moreover, none of the experimentally suggested levels had energy higher than 7.5 MeV. Contrary to the uncertain and conflicting experimental evidence, Hoyle's prediction of the 7.68 level was sharp and definite.

Ward Whaling had come to Caltech as a research fellow in 1949, and by 1952 he had joined the Kellogg group as a nuclear physicist specializing in the determination of energy levels in the lighter elements. Level diagrams were a specialty at the laboratory, where they were worked out by Thomas Lauritsen and others. Whaling recalled

[50] Arnett (2005, p. 22), who refers to the study of Malm and Buechner as the one that showed the nonexistence of earlier reported lines of about 7 MeV.

how Hoyle addressed him and his group with respect to the question of a carbon-12 resonance of the proper energy. At the time the group consisted of Whaling, William Wenzel, Ralph Pixley, and an Australian visitor by the name of Noel Dunbar.

> So we looked at Tommy's [Thomas Lauritsen's] level diagrams, and you could see that at one point somebody had penciled in a level there, but then other people had tried to see it, and then Tommy had erased it; it seemed not to exist. And its energy wasn't exactly where it needed to be, anyway, for Hoyle's purposes. It was close by—like 7.4, or something like that, instead of 7.6. But the idea immediately occurred: "Well, let's look and see if we can see such a state in carbon-12." . . . We decided to look at it by bombarding nitrogen-14 with deuterons and looking at the alpha particle. The reaction goes to carbon-12 plus an alpha particle. And by looking at the energy of the alpha particles, we should find high-energy alpha particles that leave carbon-12 in its ground state. And groups of alphas of lower energy, because some of the energy was left in the carbon-12 residual nucleus. So we decided we would try that.[51]

It will come as no surprise to historians that one has to be careful with scientists' recollections, not least when they refer to events that occurred nearly a half century earlier. This is illustrated by the time it took to verify Hoyle's prediction. In 2002 Barnes said that the experimental confirmation took "literally just a few weeks," which agrees roughly with Hoyle's recollection of "about ten days."[52] On the other hand, in 2004 Whaling, who was in charge of the experiment, recalled that the experiment took some three months.[53] Further, in an earlier conversation in about 1992 Whaling said that the first indication of an excited carbon state near 7.7 MeV was reported in his laboratory notebook on 15 January 1953.[54] We may probably conclude that the prediction was verified fairly quickly and at a time when Hoyle was still at Caltech.

Apart from being communicated at the September 1953 meeting of the American Physical Society, the study of Whaling and his collaborators was published in early November in the *Physical Review*, this time without Hoyle as a coauthor.[55] The reaction examined by the Kellogg physicists, that is, $^{14}N(d, \alpha)^{12}C$, was the same one that had been studied more than 20 years earlier by Holloway and Moore, but the experiment of Whaling and his group was far more accurate. They used a beam of 620-keV deuterons to bombard a target of nitrogen-14 in the form of frozen ammonia (NH_3) on a cooled copper plate. The energy spectrum of the emitted alpha particles was measured by means of a double-focusing magnetic spectrometer, a method far superior to the old one based on the range–energy relationship of alpha particles. Whaling's group found a value for the carbon resonance of 7.68 ± 0.03 MeV with a width less than 25 keV, in excellent agreement with Hoyle's calculations (Fig. 3). These calculations were based on astrophysical considerations, but at the time astrophysics was of no

[51] Whaling interview, http://resolver.caltech.edu/CaltechOH:OH_Whaling_W.

[52] Gregory (2005, p. 64) and Hoyle (1994, p. 264). In 1982, Hoyle (1982a, p. 3) said that the predicted state was found "a week or two" after the meeting in Fowler's office.

[53] Mitton (2005, p. 209), who quotes an e-mail from Whaling of 26 April 2004.

[54] Bartusiak (1993, p. 136).

[55] Dunbar et al. (1953). See also Spear (2002).

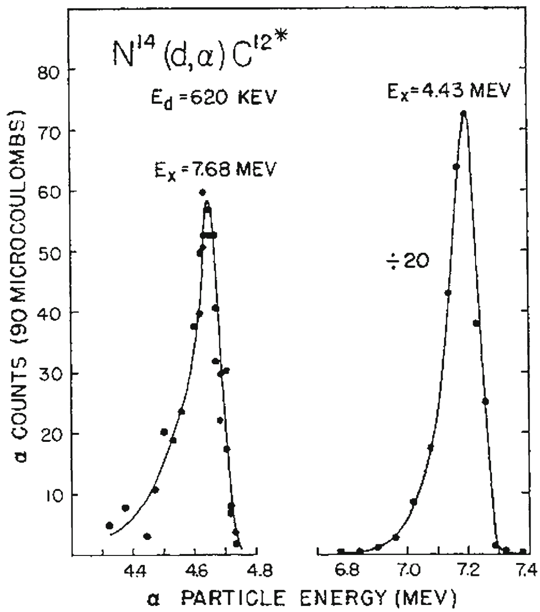

Fig. 3 The alpha spectrum showing Hoyle's resonance state. *Source* Dunbar et al. (1953)

great interest to Whaling and his collaborators who merely expressed their indebtedness "to Professor Hoyle for pointing out to us the astrophysical significance of this level." What this significance was they did not say.

Further experiments reported by Fowler and his group of nuclear physicists narrowed down the carbon-12 resonance level to 7.653 $\pm$ 0.008 MeV and showed that the spin and parity state of the level was most likely 0^+. (The ground state is also 0^+, while the first excited level of energy 4.43 MeV is a 2^+ state.) For the disintegration energy of beryllium-8 decaying into two alpha particles they obtained 93.7 $\pm$ 0.9 keV. These results were found by producing the resonance state in the beta decay of boron-12 to three alpha particles.[56] The data found by the Kellogg physicists and other groups were in full agreement with Hoyle's theoretical arguments. Further, American physicists were not alone in investigating the Salpeter–Hoyle triple alpha process; it also attracted the attention of European and Japanese theorists. For example, research groups at the universities of Tokyo and Kyoto made detailed calculations of the new triple alpha process and other alpha-capturing processes in the helium cores of stars.[57]

By the time Hoyle made his prediction he was not only busy with nucleosynthesis in the stars, he was also working on the steady-state cosmological theory that he, together with Hermann Bondi and Thomas Gold, had introduced in 1948. Indeed, he was at the time best known as a cosmologist and advocate of this controversial theory of the universe based on the hypothesis of continuous creation of matter. By its very nature,

[56] Cook et al. (1957). The 7.65 MeV level appeared in the energy-level diagram published by Ajzenberg and Lauritsen (1955, p. 113), but without mentioning its background in Hoyle's prediction.

[57] Nakagawa et al. (1956) and Hayakawa et al. (1956). For a concise account of the Salpeter–Hoyle process, see Clayton (1968, pp. 411–415).

the steady-state theory was restricted to stellar processes when it came to explaining the building up of elements, and for this reason it was important to demonstrate that all of the elements could in fact be produced without assuming a hot primordial state of the universe. Although Hoyle's study in nucleosynthesis thus had a connection to his favored cosmological model, it was not motivated by this model or otherwise closely related to cosmology. In his articles on the synthesis of carbon and other elements Hoyle was careful not to mention the cosmological debate. This was also the case when he joined forces with Fowler, Margaret Burbidge, and Geoffrey Burbidge and in 1957 published the comprehensive and soon famous study on stellar nucleosynthesis known colloquially as the B^2HF theory.[58]

Although this theory was not directly associated with steady-state cosmology, indirectly it weakened Gamow's big bang alternative and, consequently, added support to the steady-state view of the universe. To Bondi, the B^2HF theory was a "tremendous triumph" for the steady-state conception of the universe.[59] Even before the appearance of B^2HF, it was realized that the study by Hoyle and others on stellar nucleosynthesis was of relevance to the cosmological controversy. As Gold expressed it at conference on nuclear astrophysics held in Liège, Belgium, in 1953: "In comparing these two cosmological theories one finds that the theory of the original explosion loses an important advantage if it can be shown that the generation of heavy elements is in fact a current progress."[60]

5 Responses to the 7.65 MeV level

Hoyle's prediction is today recognized to be a most important contribution to the early understanding of the formation of elements in the stars. It is often assumed that it also was considered to be such in the past. The prediction and its confirmation "electrified the nuclear physics community," says Geoffrey Burbidge.[61] However, this is to greatly overrate the early influence of the resonance level and in particular Hoyle's prediction of it. Taken together, the two brief articles of 1953 in which the prediction was announced were cited 8 times between 1953 and 1981, whereas they received 62 citations in the period from 1982 to 2009.[62] There is little doubt that these citation numbers reflect the increasing popularity of the anthropic principle.

Hoyle himself does not seem to have considered the prediction as particularly important. He did not turn it into a scientific article in 1953, nor did he highlight it in his later studies. As mentioned, he appeared as coauthor of an abstract article in 1953, but without actually contributing to the article or showing any interest in it. He did not cite it in his 1954 article in *Astrophysical Journal* nor, as far as I know, in any

58 Burbidge et al. (1957); extracts in Lang and Gingerich (1979, pp. 374–388).

59 Bondi (1966, p. 400). See also Kragh (1996).

60 Gold (1954, p. 69).

61 Burbidge (2003, p. 224).

62 According to the ISI Web of Science. The two articles are Dunbar et al. (1953) and Hoyle et al. (1953). Given that the latter article has received only 41 citations over more than half a century it is hardly correct to call it a "much-cited paper" (Scerri 2007, p. 323). Salpeter's 1952 article was cited more frequently, 54 times until 1981. It should be noted that the citation data in the ISI Web of Science are not complete.

of his later research articles. In a survey of stellar nucleosynthesis given at the 1958 Solvay Congress, Hoyle pointed out the significance of the second excited level in carbon-12,[63] but again without referring to his own role or to the 1953 abstract article. "He took the news of his successful prediction calmly," as Whaling recalls.[64] Hoyle later said about the prediction and its confirmation in early 1953 that "In a sense this was a minor detail," adding that it had a disproportionate effect "because it was seen by physicists as an unusual and successful prediction."[65]

The literature on nuclear physics and astrophysics in the 1950s confirms that the 7.65-MeV level was not seen as greatly important. Not only were there few references to it, none of the references highlighted Hoyle's prediction as a very significant one. Most did not mention the prediction, but only the experimental discovery of the level. To the extent it was known, it was known mainly through oral presentations and informal discussions. Thus, at an important meeting on astrophysics at the University of Michigan in July 1953, Salpeter gave comprehensive lectures on the triple alpha process and related processes of element formation in stars. His lectures included discussion of the Hoyle resonance, but they were not published.[66]

In September 1953 an international conference on nuclear astrophysics convened in Liège, attended by most American and European experts. Among the participants were Fowler, Greenstein, Salpeter, Bondi, Gold, Oskar Klein, Evry Schatzman, and Dirk ter Haar. (Hoyle was absent both in Michigan and Liège.) Only one of the articles appearing in the conference proceedings, a survey of nucleosynthesis written by Greenstein, referred to Hoyle's prediction. Greenstein described the case as follows: "Hoyle, during lectures in 1953 at the Caltech, showed that in the absence of nuclear resonance the rate of formation of C^{12} and its destruction were such that only over a very narrow range of temperature would the ratio C^{12}/O^{16} be appreciable. Fortunately, unpublished study at the Kellogg Laboratory has now established that a low-lying nuclear resonance level exists in C^{12}."[67]

In his 1956 article with Fowler, Greenstein again pointed out the astrophysical significance of the resonance level, but this time without mentioning that it had its origin in Hoyle's prediction. The same was the case when Salpeter discussed the new version of the triple alpha process at an annual meeting of the American Physical Society in January 1955,[68] and also in a more popular article he published later the same year. Salpeter merely said that the triple alpha process proceeds "via intermediate steps involving the unstable Be^8 and a resonance level in C^{12} which was only discovered quite recently."[69] Many physicists doing calculations on stellar nucleosynthesis in the 1950s were simply unaware that Hoyle had made a prediction that was subsequently

63 Hoyle (1958, p. 284).

64 Spear (2002, p. 38).

65 Hoyle (1986, p. 449).

66 Salpeter (1957, p. 517). Participants in the Michigan summer school included Walter Baade, Allan Sandage, Geoffrey and Margaret Burbidge, Edwin Salpeter, George Gamow, Don Osterbrock, Owen Gingerich, and Vera Rubin; see Gingerich (1994).

67 Greenstein (1954, p. 319).

68 Salpeter (1955a).

69 Salpeter (1955b, p. 286).

confirmed in the laboratory. Had they missed the brief abstract in the September 1953 issue of *Physical Review*, they would not necessarily know about it. For example, a group of Japanese physicists apparently thought that the resonance level had been discovered experimentally first and then Hoyle had understood its significance in the triple alpha process: "Since a level of ^{12}C at 7.68 MeV and some properties of other nuclei were observed, Hoyle tried to calculate the reaction rates . . ., taking into account the resonance capture."[70]

In short, there is no evidence that the discovery of the Hoyle resonance "electrified" either the nuclear physics or the astrophysics community. Although it was known and appreciated by experts in nucleosynthesis, its origin as a theoretical prediction attracted little attention or was simply unknown. That only changed later.

6 Hoyle on cosmic fine tuning

Hoyle's argument that there must exist a resonance state in carbon-12 at an energy of about 7.7 MeV was a brilliant prediction based on astrophysical reasoning, and one that deservedly occupies a prominent place in the history of astrophysics. But history is one thing, folklore another. Was it an anthropic prediction? In his biography of Fred Hoyle, Simon Mitton notes that "A certain amount of folklore now surrounds the experiment [of Whaling et al.] and Hoyle's role." While this is certainly correct, unfortunately Mitton adds to the folklore in his account of how Hoyle motivated his interest in the resonance to his colleagues at Caltech:

> After studying Salpeter's paper in the Astrophysical Journal, Hoyle was not prepared to let the matter rest. . . . Fred said to his associates, "Since we are surrounded by carbon in the natural world and we ourselves are carbon-based life, the stars must have discovered a highly effective way of making it, and I am going to look for it."[71]

Another biographer of Hoyle, Jane Gregory, tells basically the same story. Referring to Hoyle's thoughts in 1953, she says: "Hoyle thought that since human beings exist to ask such questions about the universe—and they exist in their particular biological form because carbon exists in plenty—then the universe must be one in which carbon is readily made."[72] However, there is no documentary evidence at all (at least none that I know of) that Hoyle expressed himself in this or some similar anthropic way, nor that he originally thought along such a line. The two biographies, both well researched and solidly documented, repeat the anthropic myth.

Whether or not Hoyle himself came to believe that he had found evidence for anthropic fine-tuning in 1953, he did not originally see it in that way. Hoyle *might* have reasoned something like this: "Since life is known to exist, and life as we know it is carbon based, there must be a way to produce carbon in the stars. Consequently, . . . there must exist a 7.68 MeV resonance." This is what many sources, including the

70 Hayakawa et al. (1956, p. 508).

71 Simon (2005, p. 206). For a more florid folklore account, see Chown (1999, pp. 173–178).

72 Gregory (2005, p. 63).

two biographies mentioned above, claim or at least imply. In that case his reasoning would have counted as an anthropic prediction. But this was not the way Hoyle argued in 1953. In his autobiography of 1994, entitled *Home Is Where the Wind Blows*, Hoyle said that the prediction caused him to contemplate the question of whether the existence of life might be due to coincidences in nuclear physics. Perhaps, he said, "life would perforce exist only where the nuclear adjustments happened to be favorable, removing the need for arbitrary coincidences, just as one finds in the modern formulation of the WAP."[73] He also spoke of the prediction as "an early application of what is known nowadays as the anthropic principle."[74] We are not told when he began thinking along these lines, but as mentioned there is no evidence to suggest that such anthropic-like thoughts motivated his prediction. Instead of speculating of what he might have thought, it is more fruitful to look at how Hoyle expressed himself in his published studies relating to the prediction and the anthropic principle.

In the early publications on the carbon resonance, neither Hoyle nor others mentioned it as a case of fine-tuning, nor did they refer to the existence of life in the universe. A lecture given in 1957 in the University Church, Cambridge, on the relationship between science and religion might have provided an opportunity for Hoyle to make the connection, but in fact he did not. Hoyle discussed the possibility that "the laws of nuclear physics are designed to promote the origin of the complex atoms, so it may well emerge . . . that the laws seem as if they have also been deliberately designed to promote the origin of life." He went on to say: "Life demands highly special physical conditions if it is to flourish. Hence if life is part of a deliberate plan so must the origin of the physical conditions be."[75] Although Hoyle found the hypothesis of specially designed fine-tuning appealing, he did not clearly support it. What is more, he did not refer to his earlier calculation of the carbon-12 resonance as a case in point.

As far as I know, Hoyle first referred to life in connection with the nuclear processes generating carbon and oxygen in a book of 1965, where he offered an account of the delicate balance of the energy levels in beryllium-8, carbon-12, and oxygen-16. "The whole balance of the elements carbon and oxygen is critical not only for the chemistry of living organisms but for the distribution of the planets," he said.[76] He continued:

> If carbon were more abundant than oxygen it would be inevitable, I think, that a big graphite planet would lie nearest to the sun. . . . Had there not been a favorably placed resonance in the C^{12} nucleus, the rate of carbon production would be so slow that very little carbon would exist in the world; the opposite to the graphite planet situation. . . . When we examine the O^{16} nucleus we see that a level exists very close to the sum of the rest masses of C^{12} and an α-particle, but fortunately the level is *below*, so that an actual resonance can never occur. I say

73 Hoyle (1994, p. 266).

74 Ibid., p. 256.

75 Hoyle (1957, p. 65). Another contribution to the lecture series was given by Charles Pantin, a British zoologist who is sometimes mentioned as an early advocate of anthropic reasoning and the idea of multiple universes; see Barrow and Tipler (1986, p. 250).

76 Hoyle (1965, p. 147).

> fortunately, because if there was little carbon in the world compared to oxygen, it is likely that living creatures would never have developed.

At the end of his book Hoyle returned to the question of whether the placing of the energy levels in carbon-12 and nitrogen-16 was fortuitous or not:

> It could simply be that since creatures like ourselves depend on a balance between carbon and oxygen, we can exist only in the portions of the universe where these levels happen to be correctly placed. In other places the level in O^{16} might be a little higher, so that the addition of α-particles to C^{12} was highly resonant. In such a place oxygen would be overwhelmingly more abundant than carbon, and creatures like ourselves could not exist.[77]

While Hoyle did not think anthropically in 1953, his above speculations of 1965 can well be seen as an anticipation of the anthropic principle. In a textbook published 10 years later Hoyle repeated his idea, adding the speculation that the balance between the electromagnetic and nuclear forces (and hence the energy levels) might "vary from one region of the universe to other, very distant regions."[78] In that case, life as we know it would only form in some cosmic regions, evidently in our own and possibly only in ours. In neither of the publications did Hoyle connect his study of 1953 with anthropic considerations, either in the sense that he singled out intelligent life or suggested that his earlier study was anthropically motivated.

At the latest by 1980 Hoyle was aware of the anthropic principle, such as expounded in the article by Carr and Rees in *Nature* of 1979. He apparently now conceived his prediction of 1953 as related to anthropic reasoning. "Is the positioning of the level at 7.65 MeV in ^{12}C an accident?" he asked. "Is it an accident that the 7.12 MeV level of ^{16}O lies just below the sum of the rest masses of ^{12}C and ^{4}He? Without these circumstances together, the cosmic ratio of C to O would not be appropriate to life, which demands approximately equal abundances for these two crucial elements."[79] By the early 1980s Hoyle was sometimes associating his prediction of the 7.65 MeV level with the anthropic principle, but not in any explicit sense. For example, in 1982 he spoke of the energy levels of carbon-12 and oxygen-16 as a "put-up job" apparently designed to produce the two elements in the right ratio. "A common sense interpretation of the facts suggests," he said, "that a superintellect has monkeyed with physics, as well as chemistry and biology, and that there are no blind forces worth speaking about in nature."[80] He did not specifically refer to life, whether human or not.

Although Hoyle was at that time intensely occupied with the nature and origin of life, he did not endorse the anthropic principle in any of its ordinary meanings and neither did he find it to be of much use for cosmology. As he saw it, the significance of the principle lay elsewhere. In an address at the first Venice Conference on Cosmology and Philosophy in 1987, he gave a review of his ideas of the relations between

[77] Ibid., p. 160.

[78] Hoyle (1975, p. 402).

[79] Hoyle (1980, pp. 54–55). Hoyle also mentioned a few other instances of fine-tuning, referring to Carr and Rees (1979) for "a fuller compilation of these 'anthropic' issues."

[80] Hoyle (1982b, p. 16).

cosmology and biology in front of Carter, Sciama, Barrow, George Ellis, and other leading cosmologists. He emphasized that the key problem was how to explain the origin of life. According to Hoyle's reasoning, it was extremely implausible that life on Earth could have occurred by chance, which "seems to me [to] be the essence of the *anthropic principle*." As to this principle, he turned it upside down:

> Until we understand it [the origin of life], much, I believe, will remain to be discovered about cosmology, for surely the occurrence of life is the largest problem of which we are aware. It is not so much that the Universe must be consistent with us as that we must be consistent with the Universe. The anthropic principle has the problem inverted, in my opinion.[81]

This is a version of the anthropic principle quite different from the one formulated by Carter and subsequently developed by a host of other physicists, cosmologists, and philosophers. At the following Venice conference, dedicated to the anthropic principle and taking place in 1989, Hoyle apparently adopted the strong principle, but it was in a version quite different from the usual one. "If our existence leads to a potentially falsifiable prediction in the sense of Popper," Hoyle said, "then I take it that the anthropic principle is being employed in its strong mode."[82] He might have referred to his early prediction of the carbon-12 resonance as an example, but did not. Instead he derived a prediction from "the immense biochemical complexity of life" concerning the spectrum of the microwave background, which he considered "an example of a prediction from the strong anthropic principle relating the basic issue of the origin of life to the basic form of cosmology."[83] This basic form of cosmology was the steady-state theory of the universe, which according to Hoyle was in harmony with and indeed favoured by anthropic considerations. While Hoyle avoided connecting his 1953 prediction with the anthropic principle, at the same conference the French astrophysicist Hubert Reeves made the connection. Maintaining that the anthropic principle could result in predictions made from a posteriori considerations, he mentioned Hoyle's prediction as an example.[84]

Given that the standard view was and presumably still is that the anthropic principle rules out the steady-state universe and other cosmological theories operating with an infinite past,[85] Hoyle's argument at the second Venice conference underlines the unorthodox nature of his conception of the anthropic principle. The general argument that the existence of life in the universe can be understood on the basis of the anthropic principle in conjunction with a revised steady-state theory (rather than big bang cosmology) also appeared in the book, *Life on Mars?*, that Hoyle wrote with his long-time collaborator and former student Chandra Wickramasinghe. The two

[81] Hoyle (1991, p. 518).

[82] Hoyle (1993, p. 85). Popperian falsifiability is not a methodological virtue commonly associated with the anthropic principle. On the contrary, the two notions are generally seen as contradictory.

[83] Ibid., p. 88.

[84] Reeves (1993, p. 68).

[85] What is sometimes known as the Davies–Tipler argument is an alleged refutation of cosmological theories with an infinite past, including the steady-state theory, on the basis of the SAP; see Davies (1978) and Barrow and Tipler (1986, pp. 601–608).

astronomers argued that access to superastronomical masses of carbonaceous matter is to be needed to get life started, and that this favoured the new quasi-steady-state cosmology (QSSC) over the big bang theory of the universe.[86]

Hoyle now referred to the weak and strong forms of the anthropic principle in versions that were more in line with those adopted by most other authors. He suggested that the strong version was of little or no scientific value—it might be nothing but "a semantic substitute for teleology." On the other hand, he and Wickramasinghe considered the WAP—that "the universe must be consistent with the existence of life, and in particular with the existence of human life"—to be both testable and scientifically valuable. They explicitly described Hoyle's early prediction as a deduction from the anthropic principle:

> The weak anthropic principle serves to remove otherwise inexplicable cosmic coincidences by the circumstance of our own existence. One of the present writers [Hoyle] was involved in an early application of the weak anthropic principle. . . . It was shown in 1952–53 that to understand how carbon and oxygen could be produced in approximately equal abindances, as they are in living systems, it was necessary for the nucleus of ^{12}C to possess an excited state close to 7.65 MeV above ground level. No such state was known at the time of this deduction but a state at almost exactly the predicted excitation was found shortly thereafter. So one could say that this was an example of using the weak anthropic principle in order to deduce the way the world must be, although the concept of the anthropic principle had not been explicitly formulated at that time.[87]

Thus, Hoyle finally came to the conclusion that his 1953 prediction was a case of anthropic reasoning, or rather that it could be understood as anthropic in a *post factum* sense. But it took him about 40 years, and he never suggested that his motivations for the prediction were related to the existence of life in the universe. Nonetheless, Wickramasinghe later maintained that the WAP was "pioneered by Hoyle in the 1950s" when he "deduced that the nucleus of ^{12}C must possess an excited state close to 7.65 MeV above ground state."[88]

7 A case of anthropic prediction?

I have shown that Hoyle's famous prediction of the 7.65 MeV resonance state was not originally thought of in terms of anthropic fine-tuning, neither by Hoyle himself nor by other researchers involved in stellar nucleosynthesis. The early literature related to the anthropic principle did not refer to the prediction of 1953 as an example of anthropic reasoning, although it would have been tempting to use the case in the

[86] The QSSC model, introduced in 1993 by Hoyle, Narlikar, and Geoffrey Burbidge, has no beginning in time, but contrary to the classical steady-state theory it expands in a cyclic pattern and for this reason does not satisfy the perfect cosmological principle on which the steady-state model was originally based; see Hoyle (1993) and Kragh (1996, pp. 385–388) for a summary description.

[87] Hoyle and Wickramasinghe (1999, pp. 89–90). The article, which first appeared as a preprint in 1991, was also published as a chapter in Hoyle and Wickramasinghe (1997).

[88] Wickramasinghe (2005, p. 187).

controversy that began to evolve at the time. Proponents of the anthropic principle were painfully aware of its lack of predictivity; yet, they ignored the one case that would soon be regarded as an exception. For example, in 1982 Carr emphasized how much more impressive it would be "if the Anthropic Principle could be used to *predict* a coincidence," regretting that "so far this has not been done."[89] Like all astrophysicists at the time, Carr was aware of Hoyle's prediction, and yet, he did not think of it as anthropic. Nor did Carr and Rees in their article of 1979.

To further illustrate this point, consider an important article that the Princeton physicist Robert Dicke published in 1961 and which is generally regarded as one of the main sources for the anthropic principle. Dicke discussed how "the biological requirements to be met during the epoch of man" constrained cosmological knowledge, and in this context he mentioned that heavier elements must have been produced in the stars. "It is well known that carbon is required to make physicists," as he phrased it.[90] Had Dicke seen Hoyle's mechanism of carbon generation as connected to human life, it would have been natural to refer to it as his prediction. Again, Dicke did not make the connection. Only from about 1984 was the case *reconstructed* to be an anthropic prediction, and it became common to associate Hoyle's reasoning with the existence of life in the universe. Apparently Hoyle came to share this view. It was also only from this time that the case became well known outside the small community of nuclear astrophysicists.

There is no generally agreed definition of what constitutes an anthropic prediction, a concept which is used in diverse and loose ways. In an article of 1994, the philosopher John Leslie defined anthropic predictions as "predictions *encouraged* by the anthropic principle, even if not dictated by it," adding that such predictions might well be made before Carter formulated and named the principle.[91] This is a reasonable definition, but it is much less reasonable to exemplify it by Hoyle's "two dramatically successful anthropic predictions" of the carbon-12 resonance and the nonresonant state in oxygen-16. Hoyle's use of the nonresonant 7.1 MeV level in oxygen was not in fact a prediction—since the level was known at the time—but by Leslie's definition Hoyle must have been encouraged by anthropic considerations to make his prediction of the 7.65 MeV state. Indeed, Leslie maintains that "'anthropic' considerations did influence him," quoting from Hoyle that "we can exist only in the portions of the universe where those levels happen to be correctly placed."[92] But this is a quotation from 1965, twelve years after the prediction! Only if Hoyle had said something along this line in 1953 (which he did not) might it be taken as evidence that he was anthropically encouraged. Unfortunately, this kind of careless use of historical sources is not exceptional among philosophers, scientists, and science writers.

I shall here take "anthropic prediction" to mean that if a property or phenomenon of nature is (i) inferred from or inspired by the existence of (intelligent) life in the universe, and if (ii) the property or phenomenon is unknown at the time of prediction,

89 Carr (1982, p. 251); reprinted in Leslie (1990, pp. 134–153).

90 Dicke (1961, p. 440); reprinted in Leslie (1990, pp. 121–124).

91 Leslie (1994, p. 120).

92 Leslie (1994, p. 126). The quotation is from Hoyle (1965, p. 159).

then it qualifies as an anthropic prediction. If the second condition is not employed, a great variety of inferences will have to be accepted as anthropic. The same is true for the second condition: it is not enough that a prediction can be reconstructed as relating to the existence of life, the relation must actually enter into the prediction. If it can be shown that advanced life depends crucially upon a predicted property, but this played no role in the prediction, one should not speak of an anthropic prediction, but rather of an anthropically relevant or significant property.

For example, in 1931 Paul Dirac predicted the existence of positrons on the basis of relativistic quantum mechanics, and much later these particles turned out to play an important part in the early universe. It can thus be argued that had positrons not existed, neither would we. It is obviously unreasonable to call Dirac's prediction anthropic for this reason alone. As we have seen, Hoyle's prediction was novel but not based on considerations of life. Although the existence of the resonance state may be said to be anthropically significant (like Dirac's prediction may in principle be said to be), the prediction was no more anthropic than Dirac's prediction of the positron.

While there is no doubt that Hoyle's prediction was not initially conceived as anthropic, it may still be argued that it nonetheless was anthropic. One may argue, contrary to what I have suggested, that Hoyle's own motivations and the entire history of the case are irrelevant for deciding whether it is anthropic in nature. Although such a position is foreign to a historian's mind, for the sake of argument I shall grant it as legitimate. According to this line of thought, what matters is solely if the predicted state is actually a necessary condition for the existence of intelligent life. If the answer is yes, the prediction was anthropic, irrespective of how Hoyle and contemporary scientists thought about it.

More recent investigations of the energy levels in carbon and oxygen have to some extent been inspired by considerations of this sort, that is, there have been attempts to establish how finely tuned for life the levels really are. Are they *really* of anthropic significance? Of course, Hoyle's prediction refers only to the existence of carbon atoms, not to human beings. Had humans or other intelligent life forms not evolved, it would not have changed the prediction one iota (but then, of course, the prediction would not have been made!). For this reason, it has sometimes been objected that it cannot possibly be anthropic in any strict sense. However, this is hardly a valid objection, since it is generally acknowledged that the term "anthropic principle" is a misnomer: it does not refer specifically to humans, but is a selection principle that requires the universe and its history to be consistent with the conditions that are necessary for our existence as observers. Ten years after having introduced the anthropic principle, Carter regretted having suggested the term, which he now preferred to call the "self-selection principle."[93]

In a series of "experiments" in the form of computer calculations Mario Livio and his colleagues Dave Hollowell, Achim Weiss, and James W. Truran investigated in 1989 how changes in the carbon-12 resonance would affect the production of carbon in the stars. Using updated values for Hoyle's 0^+ resonance (7.644 MeV) and its place above the sum of the energies of beryllium-8 and helium-4 (277 keV), they tested the

93 Carter (1983).

consequences of a hypothetical change in the energy difference. Livio and his collaborators reported that, in the case of helium burning in the core of a massive star some 20 times as heavy as the Sun, the difference between the two energies could be increased by 60 keV without destroying the consistency with the observed abundance of carbon and oxygen. If the 7.644 level were lowered by 60 keV, it turned out that the yield of carbon would increase markedly.

Relating their results to the anthropic principle, Livio and colleagues pointed out that the 60 keV shift represents a significant fraction of the energy difference between the 7.644 level and the (^{8}Be + α) energy. Hence their conclusion: "Thus, we believe that at least some formulations of the SAP, which is based on the necessity of having the 0^+ level exactly where it is, is weakened significantly by our results."[94] In agreement with this conclusion, Steven Weinberg has observed that what affects carbon production in the stars is not really the Hoyle resonance level of about 7.65 MeV, but the energy difference of roughly 0.25 MeV between the excited state and the state of the (^{8}Be + α) system at rest. "This energy misses being too high for the production of carbon by a fractional amount of 0.05 MeV/0.25 MeV, or 20 percent, which is not such a close call after all."[95]

Later and more sophisticated calculations in the same tradition, but focusing on slight variations in the strong interactions keeping the nucleons together, have led to results that to some extent differ from those of Livio and his collaborators. In a series of studies Heinz Oberhummer and colleagues have calculated the sensitivity of the location of the resonance level to the strength of the nucleon–nucleon interaction, finding that even a small change in the strength (about 0.5%) will make carbon-based life impossible.[96] The helium in the stars will be transformed into either carbon or oxygen, but not into both elements. This and similar study has strengthened the case for fine-tuning somewhat, yet without unambiguously confirming the anthropic significance of the Hoyle resonance level. It is presumably a matter of taste how finely tuned for life a coincidence has to be in order to qualify as anthropic. As Livio and colleagues remarked in their 1989 article, the implications for evaluating the anthropic principle "are not entirely free from subjective feelings."[97]

Rather than focusing on the degree of fine-tuning, one may deny the anthropic nature of Hoyle's prediction by arguing that it has nothing to do with the existence of life. This is what Lee Smolin, an outspoken critic of string theory and the anthropic principle, has done. As he argues, the fact that we and other living beings are crucially made of carbon compounds is unnecessary for the argument, which is really nothing

[94] Livio et al. (1989, p. 284). For a sharper antianthropic conclusion based on the calculations of Livio *et al*., see Klee (2002); and for a critique of Klee's arguments, see Walker and Ćirković (2003). It is noteworthy that while Livio *et al*. and also Carter related the case of the carbon-12 resonance to the SAP, in the 1990s Hoyle saw it as an example of the weak form of the principle.

[95] Weinberg (2001, p. 237). His essay on "A designer universe?" was first published in *The New York Review of Books*, 21 October 1999, pp. 46–48. Weinberg (2007) confirms that he does not consider the Hoyle resonance as evidence for anthropic fine tuning.

[96] Oberhummer et al. (1998, 2000) and Schlattl et al. (2004). For still later and more precise investigations of the triple alpha process, see Fynbo et al. (2005).

[97] Livio et al. (1989, p. 284).

but a deduction from observed facts and the known laws of physics.[98] In the anthropic version—not to be confused with Hoyle's authentic version—the argument starts with the observation that life can only exist if carbon is plentiful in the universe. But this observation is redundant; it plays no role in the logic that leads to the prediction. Let us imagine, says Smolin, the counterfactual scenario that Hoyle's prediction had been falsified rather than verified by experiments. In that case, would we have concluded that carbon is not essential to life? Surely not; we might conclude that there was something wrong with our model of the triple alpha process, that carbon was not necessarily produced in stars alone, or even that our knowledge of stellar composition and the laws of nuclear physics needed to be reconsidered. The carbon–life connection would never be questioned.

8 Conclusion

Fred Hoyle's prediction of the 7.65-MeV resonance state in carbon-12 was a remarkable inference from astrophysics to nuclear structure, the first of its kind, and it had a significant effect on the later development of stellar nucleosynthesis and other branches of astrophysics. In following the history of the event I have pointed out that the existence of an excited state in this region was already suggested by some earlier experiments, but that Hoyle's prediction nonetheless counts as a novel prediction of a nuclear phenomenon. I have also suggested that the prediction was not seen as highly important in the 1950s, neither by Hoyle himself nor by contemporary physicists and astronomers. Contrary to the folklore version of the prediction story, Hoyle did not originally connect it with the existence of life. It is hardly the case that "Hoyle's successful prediction sparked a resurgence of interest in the old Design Argument," such as claimed by Barrow.[99] If it did, it was a much delayed spark.[100] The popular association with the anthropic principle is of a later date and has no basis in historical fact, something many authors seem to be unaware of or just do not care about. The anthropic myth, as I have called it, is widely considered a story that ought to be true, even if it is not—and it is not. Not only did the case not figure in the anthropic literature until the early 1980s, Hoyle himself did not conceive it as anthropic until about that time.

I conclude that from a historical point of view it is misleading to label the prediction of the 7.65 MeV state anthropic or to use it as an example of the predictive power of the anthropic principle. Whether the principle has such power remains a contested issue, but this more general question is beyond the scope of this article. Admitting that there is a certain arbitrariness in the notion of anthropic prediction, I have argued that it can

98 Smolin (2007, pp. 340–341). For further philosophically based critique of the anthropic carbon-12 claim, see Mosterin (2004).

99 Barrow (2002, p. 157).

100 Owing to its connection to fine-tuning and design arguments, Hoyle's prediction often turns up in religious contexts. Thus, in a defense of natural theology, Owen Gingerich, an astronomer and historian of science, says: "Hoyle predicted that there must be something special about the carbon nucleus, . . . something that would account for the high abundance of carbon in the universe." He adds: "I am told that Fred Hoyle said that nothing shook his atheism as much as this discovery." (Gingerich 2006, p. 57).

best be understood in a historical sense. Even if Hoyle's prediction is considered from an ahistorical point of view, there are reasons to doubt its anthropic nature.

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