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Fred Hoyle's major work in the context of astronomy and astrophysics today

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1.1 Hoyle's major contributions

It was a great privilege to be asked to open the proceedings for the Hoyle science retrospective. I went to the Institute in the second year of its existence in 1968, and then for five consecutive years until Fred resigned. Since then I have gone less often, but it is always a great pleasure to do so. In many ways Fred could have no more fitting memorial than this Institute, which continued to grow in stature even after Fred resigned, and I am sure it will continue to do so.

The organizers asked me as a former close friend and colleague of Fred, but one who is an observing astronomer, to summarize work which is largely theoretical. I presume that this is because they wanted a broad-brush overview of the main themes of Fred Hoyle's research. These are:

- Accretion 1941–47
- Stellar structure and evolution 1942–64
- Nucleosynthesis 1946–74
- Cosmology 1948–2001
- Interstellar dust 1962–2001

There is also another thread to his research, panspermia, etc. in the years 1974–2001, which is less directly related to his time in Cambridge, and which I shall not describe here.

1.2 Accretion theory

The first theme in Fred's work was accretion, with a number of studies published in the 1940s. Hoyle and Lyttleton (1941) and Bondi and Hoyle (1944) suggested that accretion of interstellar gas would increase the masses of stars significantly during their lifetimes. Also there was the suggestion that the solar corona is the result of accretion, resulting from convective dissipation (Bondi, Hoyle and Lyttleton 1947). While accretion by normal stars is no longer thought to be very important, some stars do continue to accrete matter after they are formed. In that sense accretion is still an important topic in stellar physics, and, modified by ambipolar diffusion of magnetic fields, is now thought to be important in the late stages of star formation.

Accretion is also important in considering how the first massive stars in the Universe formed at redshifts $z \sim 6$–15. These stars produced the first heavy elements, a theme in which Fred was very interested in his later work. According to computer simulations it appears that these stars first formed as a nucleus and then grew by intergalactic gas falling in on the seeds.

1.3 Stellar structure and evolution

One of Fred's major themes for several years was stellar structure and evolution. His first work in this area was on the structure of red giants (Hoyle and Lyttleton 1942). In 1945, in the days long before global relaxation methods were introduced into astrophysics, he introduced a new method for solving the equations determining the structure of a star with a convective core. Rather than integrating from the centre outwards, as was the practice of the time, and thereby suffer having to deal with the extreme sensitivity of the solution near the surface to variations in the initially unknown conditions at the centre, Fred integrated inwards appropriately sealed equations that depend on only a single parameter and are not so stiff, the parameter being determined iteratively by matching onto a solution of the Lane–Emden equation representing the convective core (Hoyle 1945).

One of the great accomplishments for which Fred is still renowned is the theory of nucleosynthesis in stars. It was a prediction of the rate of the triple-α reaction to form ^{12}C, which had earlier been worked on by Salpeter. A modification was introduced by Hoyle in 1953, which involved predicting the existence of an excited state in the ^{12}C which resulted in a higher rate for the $3\,^4\mathrm{He} \rightarrow {}^{12}\mathrm{C}$ reaction, and a slow-down for $^{12}\mathrm{C} + {}^4\mathrm{He} \rightarrow {}^{16}\mathrm{O}$. This is explained in more detail by Dave Arnett in these proceedings. This enabled the Universe to save itself from becoming mostly oxygen, and kept a significant amount of carbon to produce life.

Later Hoyle and Schwarzschild (1955) calculated the evolution of Population II stars from the main sequence to red giants. These stars are found in globular clusters, and are thought to be the oldest stars in the Galaxy. The result of these calculations was the first accurate measurement (or, perhaps, statement) of the age of the oldest stars in the Galaxy. The background to this work, the work itself and its repercussions are discussed in considerable detail in these proceedings by John Faulkner.

At about that time Fred Hoyle returned to England and began to use digital computers to calculate stellar structure (Haselgrove and Hoyle 1956, 1958). Those who have read *The Black Cloud* will remember that the progress of the black cloud was calculated on a computer using machine language. This is a difficult task, and the description is based on the personal experience Fred had in calculating stellar interiors.

As a result of their calculations, Fred and his collaborators produced the standard picture of red giants: these stars have isothermal, inert, helium cores, thin hydrogen-burning shells, and extended convective envelopes. They also arrived at realistic ages, of about 10 billion years, for the oldest Galactic stars.

Later, Fred collaborated with W. Fowler, and they were the first to note the roles of Type I and Type II supernovae in making heavy elements. They correctly surmised that Type I supernovae arise from the explosion of degenerate matter, of the type found in white dwarfs. We now believe that such supernovae occur in binary systems. Type II supernovae arise from the implosion and subsequent explosion of non-degenerate stellar cores (Hoyle and Fowler 1960; Fowler and Hoyle 1964). This remains the standard picture of supernova explosions today, with the exception that in those early days the role of neutrino transport was not realized, and the sites of the e-process and the r-process were incorrectly assigned.

1.4 Nucleosynthesis in stars

The work that I personally admire most in all of Fred's many achievements is that on nucleosynthesis in stars.

By the mid 1940s heavy elements were thought to originate in an initial dense hot phase of the Universe, and it was Fred who first realized that stars can produce heavy elements and that these can be spread into the surrounding interstellar medium by explosive processes or by stellar winds. He was also the first to realize that in massive stars which evolve to have very hot dense interiors statistical equilibrium would produce the iron-peak elements (later dubbed the 'e-process'). This, followed by explosive ejection, would enrich the interstellar gas in these elements (Hoyle 1946). This work focused people's attention on the idea that all heavy elements are made from hydrogen by nucleosynthesis in stars. This is the standard paradigm today, except for D, ^{4}He, ^{3}He, ^{7}Li, most of which is produced in the hot Big Bang.

This work was followed by the suggestion (Hoyle 1954) that the synthesis of carbon to nickel is due to successive thermonuclear buildup from hydrogen in hotter and hotter stars.

In 1957 Burbidge, Burbidge, Fowler and Hoyle wrote an amazingly prescient review article (Burbidge *et al.* 1957) on the general question of the abundances of the elements. This review contained a large amount of original work, and a systematic discussion of the many processes involved. These were the alpha process (helium capture); the e-process described above; the r-process, which is the addition of neutrons to iron-peak elements on a rapid timescale; the s-process, which is the same on a slower timescale; the p-process for the addition of protons to nuclei; and the x-processes for the production of the light elements Li, Be, B. This landmark paper came to be known as 'B^{2}FH'.

When I first went to Caltech in 1959 to work on the abundances of the elements in stars, almost every talk and seminar in the subject began 'According to B^{2}FH . . . '. The speaker might then go on to say that something in B^{2}FH was wrong, but usually the conclusion was that for the aspect they were considering B^{2}FH was correct.

B^{2}FH still provides the framework for present-day discussions of cosmic element abundances. While there have been modifications to the ideas that were put forward then, there have been no revolutionary different descriptions. The question of the site(s) of the r-process is a very active current field, particularly for the oldest stars. For an extended review of the situation 40 years after B^{2}FH see Wallerstein *et al.* (1997).

Somewhat later, Fowler and Hoyle (1960) began the science of nuclear cosmochronology, which extends to the Cosmos the ideas that had been used in geochronology to age-date systems. Using particularly the long-lived isotopes of Th and U, they inferred an age for the Universe of 11 billion years.

Hoyle and Fowler (1960) also studied nucleosynthesis in supernovae. One of their innovations was the realization that, at very high temperatures of $\sim 10^9$ K, pair production of neutrinos and antineutrinos, and positrons and electrons would cause a massive star to become unstable (Fowler and Hoyle 1964). This is particularly important for the study of the first stars, which must have zero metallicity. These stars are now thought to be massive, and could in some cases destroy themselves completely and leave no remnant as a result of this 'pair instability'.

1.5 Cosmology

Fred's contribution to cosmology is what he was best known for by the general public. In 1948 he, and Bondi and Gold, in two separate papers (Hoyle 1948; Bondi and Gold 1948), put forward the idea that the Universe is in a steady state. Fred's contribution was the introduction of an extra term $C_{\mu\nu}$ into the Einstein field equations. This extra term represents the creation of matter. At least initially the form in which matter was created was not specified, although of course it had to be electrically neutral. More recent theory, which explains the isotropy and homogeneity of the Universe, namely the 'inflation' theory, has a metric which is identical to that of the C-field cosmology.

During 1955–65 there was the controversy over the radio-source counts. This topic is covered more fully in Malcolm Longair's contribution to this volume. In fact, there is very little written by Fred about the radio-source counts having a power law slope steeper than the -1.5, which is the Euclidean value. However, Fred did suggest that the angular-diameter vs. redshift relation for radio sources could be used to distinguish the Steady State from the evolving Einstein–de Sitter cosmologies without appealing to source counts (Hoyle 1959). Moreover, he did point out in papers with Narlikar (Hoyle and Narlikar 1961, 1962) that a modification of the Steady-State theory could give $\log N$–$\log S$ slopes steeper than -1.5, and so the theory survived the requirement of observations.

The idea that massive objects and relativistic objects in galactic nuclei play a role in explaining the violent phenomena which were discovered through radio astronomy was introduced by Hoyle and Fowler (1963), and Hoyle, Fowler, Burbidge and Burbidge (1964). They did not involve black holes explicitly, but there was certainly the notion that objects in which general relativity is important are involved. This is a view that we now believe is correct.

A major contribution that Hoyle made to cosmology was on the production of the light elements. In a paper in *Nature*, Hoyle and Tayler (1964) suggested that all of the helium in the Universe could be produced in an early dense phase in the Universe or in massive stars. Later Wagoner, Fowler and Hoyle (1967) produced a detailed paper in which the synthesis of D, ^{4}He, ^{3}He, ^{7}Li was discussed, and found to be in accord with microwave background temperature. There was also the proviso that the same results could probably come from massive stars at high temperatures. This paper began the industry of calculating the cosmological density parameter from the abundances of the light elements. In a much later paper (Burbidge and Hoyle 1998) it was concluded that synthesis of the light elements in stars is possible.

Fred spent quite some time, particularly later in his career with Burbidge and Narlikar, modifying the Steady-State theory, because in some instances it was not in accord with observations. The three became interested in quasars, and suggested a 'local' hypothesis, in which quasars are ejected at relativistic speeds from nuclei of nearby galaxies (Hoyle and Burbidge 1966). Hoyle and Narlikar (1972) produced a conformally invariant gravitational theory in which the Universe has 'another side' prior to the Robertson–Walker singularity. Hoyle and his collaborators also considered modifications to the Steady-State theory that would be consistent with the extreme isotropy of the microwave background. One possibility proposed was that the isotropy is the result of thermalized stellar radiation from the dense epoch as the Universe passed from the 'other side', and could be linked to the cosmic helium abundance (Hoyle 1975). Another, in 1980, was a revision of the theory in which new galaxies are generated in a series of small bangs. One interesting modification was a quasi-Steady State, with a major creation event when the Universe had a mean density of 10^{-27} g cm^{-3} (Hoyle, Burbidge and Narlikar 1993).

Hoyle and collaborators struggled for several years to explain the general isotropy of the microwave background and the small fluctuations on large angular scales discovered by COBE in terms of the Steady State or its modifications. All involved thermalizing starlight using ingenious mechanisms (e.g. iron or graphite whiskers), but none were really successful.

1.6 Interstellar dust

Interstellar dust may sound less grandiose a topic than the nature of the Universe and the origin of the elements, but it is very important for several reasons. For example, it appears that dust can be formed in the atmospheres of even the earliest stars, and that light from galaxies even at the earliest times in the Universe suffers from dust extinction. This makes it very hard to obtain a complete census of galaxies during the first phases of their evolution.

The first piece of work in this area was by Hoyle and Wickramasinghe (1962), who suggested that graphite particles are an important constituent of dust grains. This was then followed by a paper pointing out the importance of graphite–ice grains for ultraviolet extinction (Hoyle and Wickramasinghe 1963). Together with Don Clayton, Hoyle and Wickramasinghe made, in 1975, the first suggestion that the interstellar particles, which we can study physically when they are found in meteorites, actually have their origin in the atmospheres of novae and supernovae. Before that it had been thought that dust grains were assembled in interstellar space.

Fred was a pioneer in the early use of infrared spectra to investigate dust properties. He was one of the first to realize that some of the infrared spectral features could be due to organic compounds as well as the silicates and water, which had already been identified (Wickramasinghe, Hoyle and Nandy 1977). Further work involved polysaccharides (hydrocarbons) in grains (Hoyle and Wickramasinghe 1977), and the realization that the 2200A feature in the infrared spectra is not due just to graphite particles (Wickramasinghe, Hoyle and Nandy 1977).

Fred's work on dust is also relevant in a more recent context because at high redshifts we can determine the abundances of heavy elements in the interstellar matter in very distant galaxies. However, these abundances are modified by the degree to which each of these separate elements is taken up into dust grains and so taken out of the gas phase. So considerations about the formation and chemistry of dust grains that were initiated by Hoyle and Wickramasinghe all those years ago remain important today.

1.7 Concluding remarks

My first knowledge of Fred was on the radio when I came home from the Scunthorpe Technical High School one evening in February 1950. Then I heard Fred first broadcast in what became a series of six talks on the nature of the Universe. It was at that time that I realized that even people from Scunthorpe with accents like mine could do this kind of work, a realization for which I shall forever be grateful to Fred.

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Sir Fred Hoyle and the theory of the synthesis of the elements

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Some of Fred Hoyle's pioneering ideas about the site and the nature of the synthesis of the elements are examined in a modern context of theory, experiment and observations. Hoyle's ideas concerning the nucleosynthesis cycle of stellar birth and death, rotational instability of supernovae, the onion-skin model of presupernovae, neutronization, nuclear statistical equilibrium and core collapse, thermonuclear supernovae, nucleosynthesis processes and freeze-out are discussed. The history of the clash of theory and experiment on the second excited state of ^{8}Be and helium ignition in red giants is reviewed.

2.1 Introduction

Sir Fred Hoyle (1915–2001) was the architect of the theory that the naturally occurring nuclei were synthesized from hydrogen by thermonuclear burning in stars, and especially in supernova explosions (Hoyle 1945). Today we would modify this slightly to include some primordial ^{4}He along with traces of deuterium, ^{3}He, and ^{7}Li from the Big Bang (Wagoner, Fowler and Hoyle 1967) as the original fuel for synthesizing the rest of the nuclei. Many of his ideas were already contained in two early papers, Hoyle (1946) and Hoyle (1954), which preceded the famous paper by Burbidge, Burbidge, Fowler and Hoyle (1957) and later work with W. A. Fowler (especially see Hoyle and Fowler 1960 and Fowler and Hoyle 1964).

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It is now possible to test these ideas: by direct experiment, by improved observation and by numerical simulation. We shall examine a few of the most spectacular examples.

2.2 The stellar cycle of nucleosynthesis

Work on accretion of interstellar gas by stars (Hoyle and Lyttleton 1941 and Bondi and Hoyle 1944) led to a study of how the properties of such material could lead to its condensation into stars in a galactic context (Hoyle 1945). The idea that stars were formed by accretion of interstellar gas in turn led to the idea that the subsequent generations of stars and their nucleosynthesis was an ongoing process (a 'nucleosynthesis cycle') in the evolution of galaxies (Hoyle 1946), unlike the 'one shot does it all' ideas of nucleosynthesis then common (e.g. Chandrasekhar and Henrich 1942 and Alpher and Herman 1953).

Figure 2.1 captures this nicely. The small ringed object near the centre of the image is the remnant of Supernova 1987A in the Large Magellanic Cloud.

Figure 2.1 Star formation and Supernova 1987A in the Large Magellanic Cloud (Hubble Heritage image: NASA/STScI).