Fred Hoyle's Universe

Jayant V Narlikar

This article recalls some of the seminal contributions to astronomy made by Fred Hoyle. His ideas were thought to be unrealistic at the time they were proposed, but have now been assimilated into mainstream science. A general comment that emerges from such examples is that highly creative individuals who are far ahead of their times do not get the recognition they deserve once their ideas are rediscovered and accepted as standard: for, by the time this happens, they and their contributions are forgotten.

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1. Introduction

Fred Hoyle was arguably the most imaginative astrophysicist of the 20th century. He contributed very original ideas to astronomy and astrophysics in topics ranging from the solar system to cosmology. He also made contributions to fundamental physics, in particular to the concept of action at a distance. His studies on exobiology evoked the most opposition from the Establishment because their implications were so far reaching. This article presents glimpses of the work of this multifaceted personality who is also known to the common man as an accomplished science populariser and writer of science fiction.

An indication of the emerging personality was given by an episode in Fred Hoyle's life when he was in a primary school in his native place of Bingley in Yorkshire. His class teacher asked all the children to collect specimens of a particular flower stating that the flower was known to have five petals. When the kids came back with their samples, Fred produced one specimen with *six* petals. He argued that if he had one with four petals he could

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reason that one petal had fallen off. But how could he explain an extra petal? Did it not show that the rule of five petals was not always adhered to? The teacher was annoyed at being contradicted and smacked Fred on his left ear as a punishment. After he recovered from this stinging blow, Fred asked permission to go out. Normally such a request was made for going to the toilet and as such never denied. However, leaving the class Fred went home. To his surprised mother he declared that he would never go back to the school where he was wrongly chastised.

Fred's mother listened to his story and saw the flower which Fred had kept as vital evidence. Yes, she agreed with his case and went to complain to the Headmaster. He listened to Fred's complaint and also talked to the teacher. He felt that Fred had justice on his side, but since the teacher refused to express regrets, he saw reason for Fred's resolve. As the rule in Britain demanded that every child must attend school, Fred obviously could not stay at home for ever. However, as he was due for the next (secondary) school at the end of the school year, the Headmaster got permission for him to study at home for the rest of the academic year.

This episode shows how Fred was an observant child with a firm resolve for defending views formed from direct observation even if they ran counter to the view of the Establishment. As he grew up he was to encounter several such conflicts even in the objective world of science. It will be hard, in fact impossible, to do justice to all his contributions in a single article. So we will concentrate on a few.

2. Molecular Astronomy

In the 1940s, the budding science of radio astronomy began to reveal cosmic sources of radio waves. Jan Oort in the Netherlands took the early observations seriously and asked his research student H C van de Hulst to use atomic physics and work out possible emission wavelengths observable through radio techniques. In 1944 the student came up with a possible answer: the transition in the spin state of the electron in the H-atom from a state parallel to antiparallel with respect to the spin direction of the nuclear proton leads to the emission of a quantum of frequency 1.42×10^9 cycles per second. In terms of wavelength, this corresponds to approximately 21 cm. Oort then set up a project to look for this radiation in the galaxy and by 1951, he and C A Muller managed to detect this radiation. A few days earlier H L Ewen and E M Purcell had also detected the 21-cm spectral line in gas clouds in the galaxy [1].

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For a considerable period, this discovery followed by others in different directions of the galaxy led to the realization that neutral atomic hydrogen is ubiquitous in the galaxy. In the mid-fifties, Fred Hoyle took stock of these data and proposed that the galaxy may contain not just neutral hydrogen but also *molecules*. (In fact, the first theoretical prediction of interstellar molecules was made by Hoyle and R A Lyttleton much earlier, in 1940.) According to Hoyle, clouds of molecular gas may exist in the interstellar space. He gave a well-reasoned argument for his proposal. However, when he sent it for publication, the physics and astronomy journals both rejected his paper as too outlandish. The general feeling in the scientific community was that nothing more complicated than neutral atomic hydrogen can exist in the (hostile?) interstellar space.

Hoyle wrote a science fiction novel *The Black Cloud* in which molecular clouds were described. In fact the story had one such cloud approach the Earth to charge itself with energy from the Sun!

Undeterred by this rejection, Hoyle found another avenue for publicising his idea: a channel more dramatic than a research paper. He wrote a science fiction novel *The Black Cloud* in which molecular clouds were described. In fact the story had one such cloud approach the Earth to charge itself with energy from the Sun! This novel became very popular and the idea of molecular cloud caught on in the popular mind.

Figure 1. Orion Nebula, a molecular cloud.
Courtesy: NASA/JPL – Caltech. http://photojournal.jpl.nasa.gov/jpeg/P1A01322.jpg

In 1963, S Weinrab, A H Barrett, M L Meeks and J C Henry made the radio detection of the hydroxyl (OH) molecule. Later with the development of 10–12 metre diameter antennas, more and more molecules began to be detected and Fred's concept of molecular clouds in the galaxy was fully vindicated. The new technology used millimetre waves for detection because internal transitions in molecules (changes in rotational or vibrational states) result in the emission of such waves. Also, just as finger prints identify individuals, the precisely measured wavelength of the radiation received identifies the molecule that it came from.

3. Stellar Evolution

In the 1920s, Arthur Stanley Eddington [2] worked on models of stars like the Sun, writing down equations describing the equillibrium of the star, its energy transport, the equation of state of matter in the form of plasma and radiation flowing outwards and the rate at which nuclear reactions in its core generated energy. The surface of the star could be observed spectroscopically and the equation of inonization set up by Meghnad Saha helped formulate boundary conditions for these differential equations. Although simple models could be obtained by analytical methods, in the early 1940s Hoyle realized that the details needed computers to work out. At that time numerical techniques existed for solving differential equations, but electronic computing belonged to the future.

Nevertheless, with mechanical devices, Hoyle could make progress in the field and with R A Lyttleton and later with Martin Schwarzschild, he was able to formulate stellar models both for Sun-like stars on the 'main sequence' or on the 'giant branch'. I will discuss his work on the energy production in red giants later. Here I want to emphasise his perception that real progress in our understanding of stars would come only with the availability of fast computers. I recall that around 1958–59, when as a student in Cambridge, I was introduced to the then large computer called the 'EDSAC', I was shown how to programme it in primitive machine language and type the instructions on a punched paper tape. Although minor errors could be patched up, significant ones required retyping the whole sequence of instructions. Hoyle's requirements could not be met by a computer at this level of technology. After trying unsuccessfully to get a state-of-the-art IBM 7090 for the university campus, he hired time on one in London.

Hoyle's student and my fellow-graduate student John Faulkner tackled his PhD problem on this computer. Later, in 1967 when he established his own institute in Cambridge, Hoyle installed a computer on the premises. Such was its efficacy that other departments in the university began requesting time on it in preference to the university's own computer. With relative advantages of space and speed in the new computer, Hoyle could tackle realistic physical models of stars rather than their mathematical idealizations. Thanks to his work on stellar structure and evolution, this subject is now considered the best understood part of astrophysics.

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4. Stellar Nucleosynthesis

The model of the Sun as per Eddington's picture was centred on the nuclear energy generation in the core of the star at high temperature. The thermo-nuclear reactions eventually convert four hydrogen nuclei into a helium nucleus along with some leptons and radiation as per the following reaction:

$$4^1\mathrm{H} \rightarrow \ ^4\mathrm{He} + 2e^+ + 2\overline{\nu} + \gamma \ .$$

The radiation coming from the Sun owes its origin to this reaction. As smaller nuclei like hydrogen combine to form a bigger nucleus like helium, this process is called *nucleosynthesis*. The process takes place provided the hydrogen fuel is of sufficiently high temperature. In the Eddington model this is possible only in a small central region.

What will happen when all the hydrogen in the core is exhausted? Will the star cease to shine? While the reaction is going on, are the pressures adequate to oppose the contracting force of gravity and keep the core in equilibrium?

Calculations showed that with the stoppage of nuclear energy generation the core pressure will fall and this would lead to a contraction of the core due to the force of gravity. However, when gas is compressed, it heats up and the core temperature rises; there emerges the possibility of a second nuclear reaction taking place. Since now a few hydrogen nuclei are left, they can combine with the helium nuclei to make a nucleus of atomic mass 5. Or two helium nuclei can combine to make a nucleus of atomic mass 8. Unforunately, both these nuclei are unstable and break apart soon. Thus they cannot be used for nucleosynthesis. Ed Salpeter suggested a *three*-body encounter in which three helium nuclei come together and get converted to the carbon nucleus. However, it was difficult to visualize three-body collisions as they are very rare and it was also not clear that they would result in the creation of energy required by the star to make it shine.

This was when Hoyle had a brainwave and came up with a *tour de force*. He argued that the rarity of a three-body collision may be compensated by the fact that the resulting reaction is a *resonant* reaction. In a resonant reaction there is an exact match in the combined energy of the three alpha particles, that is, the helium nuclei with the energy of the carbon nucleus. Hoyle's calculations led him to the conclusion that this trick would work if there is an excited state of carbon nucleus with the required energy. He therefore approached experimental nuclear physicists urging them to look for such an excited nucleus. They were sceptical at first. However, Ward Whaling and his colleagues at Caltech did the experimental search and found the nuclear state of carbon with *exactly* the desired level of energy.

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So Hoyle's solution of the problem was the reaction in the form of a triple-alpha encounter (three helium nuclei interacting to form an excited carbon nucleus, shown here with an asterix):

$$^{4}\mathrm{He} \rightarrow \ ^{12}\mathrm{C}^{*} \rightarrow \ ^{12}\mathrm{C} + \gamma.$$

Notice that the excited carbon is not stable and it eventually decays to the normal carbon, releasing the energy stored in the excited state. Thus we not only have a resolution of the rarity problem of the original reaction, but we also have an exothermic reaction with the generation of energy that is now at the disposal of the star.

The energy is radiated by the star while the changed circumstances lead to a rearrangement of its internal structure. As we saw earlier, the core shrinks from its original size while, with the injection of the above newly created energy, its envelop would expand. This expansion makes the star grow several times in size. These

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are the so-called *giant stars*. As and when the Sun gets into this mode, it will gobble up the inner planets, including the Earth! Also, as they expand, their surface area increases and as the energy being radiated by the star is constant, the application of the laws of thermodynamics tells us that the surface temperature of the star would fall. As the radiation temperature is related to colour, with high temperature corresponding to the violet-indigo-blue colours and the low temperature to the red colour, the star appears reddish. Hence the name 'red giant'. Several red giants are known observationally: the most familiar one is Betelgeuse, whose radius is some 700 times the radius of the Sun.

5. The B^2FH Work

In making the prediction of an excited carbon nucleus, Hoyle was concerned with the idea of making *all* the chemical elements and their isotopes in stellar processes. When the programme hit a solid wall, Fred found that his solution offered a route to bigger nuclei and he was encouraged to speculate on the grand design of making *all* the elements in stars as they evolved. In this ambitious venture he was joined by Margaret and Geoffrey Burbidge who were working as post-doctoral fellows in the United States and Willy Fowler from Caltech. They all brought their expertise to the combine: Margaret was an excellent optical observer, Geoffery was likewise good at theoretical astrophysics while Willy was a nuclear astrophysicist. And Fred, of course, was in the role of an 'idea generator'. This four-author combination is often known as B^2FH. Their mammoth study of the various stages of a star's life and working out which nuclei would be manufactured when and where, appeared in the *Reviews of Modern Physics* in 1957.

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We saw that helium synthesis to carbon occurs in the red giant star. For obvious reasons, B^2FH called the process the *triple-alpha process*. The next development

Figure 2. B^2FH: Margaret Burbidge, Geoffrey Burbidge, William Fowler and Fred Hoyle, shown here from left to right.

comes when most of the helium is finished and the star once again finds itself 'energyless'. The same effect as before now follows: the core contracts and heats up till a new high in temperature is reached when the next thermonuclear reaction takes place:

$$^{4}\mathrm{He} + {}^{12}\mathrm{C} \rightarrow {}^{16}\mathrm{O} + \gamma,$$

that is, now the nucleus of oxygen is formed. This process is called the *alpha process* and it repeats itself in successive stages as the series of nuclei with atomic mass increasing by 4 is formed:

$$^{12}\mathrm{C},\ {}^{16}\mathrm{O},\ {}^{20}\mathrm{Ne}, ...\ {}^{28}\mathrm{Si}\ ...\ [\mathrm{Fe}, \mathrm{Co}, \mathrm{Ni}].$$

Notice that the process terminates at the iron group of nuclei close to atomic mass 56. These nuclei are the stablest and have the largest nuclear binding energy. The alpha process cannot proceed beyond this stage.

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We will not go into details of how heavier nuclei are made and how they are ejected from the deep interiors of stars when they explode (for details see [1]). We end this section with an observation by Fred on why he felt so strongly that the triple-alpha process should work via a resonant reaction. As we see above, the route to forming all the remaining elements inside stars is clear *provided* the triple-alpha process delivers carbon. That we as human beings exist here on Earth, implies that all these elements of which we are made must somehow be

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Thus Hoyle was the first to bring in anthropic arguments into the picture: arguments that say that a certain behaviour of physical laws was needed because we (the humans: anthropoids!) are here to observe their effects. As we saw, he used this argument to make a clear and quantitative prediction about the existence of the excited state of carbon, a prediction that was experimentally borne out. By contrast, although the same philosophy drives the so-called *anthropic principle* today, its applications are confined to justifying the values of physical constants *which are already known.* It has so far not made a single prediction of something not previously known to physics.

6. Hoyle and Cosmology

We now come to cosmology, an area in which Fred Hoyle's contributions are considered controversial. We will demonstrate, however, that many of the ideas he proposed were controversial at the time they were proposed; but in later years they got assimilated into mainstream physics or cosmology. We will refer to the mainstream cosmology as 'the standard cosmology' and it will be taken to mean that the universe was created in an enormous explosion (referred to as the 'Big Bang') and it is today seen as expanding in all directions. Thus the distance between any two galaxies is increasing, i.e., seen from any galaxy, the rest appear to move away. Moreover, it is found that the relative speed of recession between any two galaxies is proportional to the distance separating them. First discovered in 1929 by Edwin Hubble, this result is known as *Hubble's law.* The simplest explanation of this large-scale behaviour of the universe was given by Einstein's general relativity and it leads to the conclusion that such an expanding universe originated in a Big Bang.

Figure 3. Hermann Bondi, Tommy Gold and Fred Hoyle, three creators of the steady state theory.

In 1948, Hermann Bondi, Tommy Gold and Fred Hoyle proposed a serious alternative to the standard Big Bang cosmology. They conceived of a universe whose large-scale physical properties do not change with epoch. Such a universe is without a beginning and without an end, in which the large-scale behaviour of matter and radiation is always the same. Bondi and Gold enunciated a 'Perfect Cosmological Principle' (PCP) which guarantees that the universe on the large scale is unchanging in space and time. This is why the model of the universe is called the 'Steady-State Model' (SSM). Such a universe expands and maintains a constant matter (and radiation) density despite expansion, by having a continuous creation of matter. While Bondi and Gold [3] preferred to deduce the above behaviour of the universe from the PCP, Hoyle sought a more manifestly physical framework for creation of matter. First suggested by Maurice Pryce, this concept requires the introduction of a scalar field C of *negative energy*. The Einstein field equations are then modified by the introduction of the energy tensor for the C-field.

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The negative energy aspect is needed in order to ensure adherence to the law of conservation of energy and matter. The concept was not unknown to physics. In Newtonian physics, gravitational energy is negative, for example. While there was no obvious problem in having a negative energy field, the general response to this idea

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from the physicists was negative. While trying to publish a paper on this idea, Hoyle first tried the journal, *Physical Review*. The paper was rejected for the rather strange reason of 'shortage of paper'. Hoyle [4] subsequently published it in the astronomy journal, *The Monthly Notices of the Royal Astronomical Society*, where the paper by Bondi and Gold had already appeared.

A detailed account of the SSM may be found in textbooks. An introductory discussion is found in Bondi's classsic book *Cosmology* [5]. For a more detailed study see this author's textbook *An Introduction to Cosmology* [6]. We will now highlight the contributions Hoyle made to cosmology and astrophysics against the background of the SSM.

First, we note that in the 1960s, particle physicists considered negative energy fields to be unphysical and irrelevant to theories dealing with reality. That perception has changed today and we have a lot of work going on today on the applications of *phantom fields* to cosmology. And these phantom fields are the same C-field in another garb!

7. Interaction of Particle Physics with Cosmology

It is generally assumed that particle physicists and cosmologists first got together in the 1980s with the latter using ideas from particle physics at very high energy in order to address issues like the origin and evolution of large-scale structures. The currently popular subject of 'astroparticle physics' seeks to study the universe closer and closer to the big-bang epoch when it contained ensembles of particles of ultra high energy. However, the first cosmology to draw heavily on particle physics was the steady-state cosmology, which explored this frontier area in 1958 at the Paris conference on radio astronomy. The 'hot universe' of Gold and Hoyle [7] was the outcome. Briefly, the idea is as follows:

In steady-state cosmology, the universe maintains a steady density despite expansion, by continuous creation of matter. The amount of matter expected to be produced was estimated to be extremely small, at a rate $\sim 10^{-46}$g cm^{-3}s^{-1}. Nevertheless, the question was, in what form did this new matter appear? Gold and Hoyle proposed the hypothesis that the created matter was in the form of neutrons. The creation of neutrons does not violate any standard conservation laws of particle physics except the constancy of the number of baryons. Although this was considered an objection in 1958, today the number of baryons is no longer regarded as strictly invariant. Indeed, scenarios based on non-conservation of baryons are being proposed in the context of the very early universe to account for the observed number of baryons in the universe [8].

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In the Gold–Hoyle picture, the created neutron undergoes a β decay:

$$n \to p + e^- + \bar{\nu} \ .$$

The conservation of energy and momentum results in the electron taking up most of the kinetic energy and thereby acquiring a high kinetic temperature of $\sim 10^9$ K. Gold and Hoyle argued that such a high temperature produced inhomogeneously would lead to the working of heat engines between the hot and cold regions, which provide pressure gradients that result in the formation of condensations of size ≥ 50 Mpc. Such a result follows from the details of the beta-decay process and the SSM. It was already known that pure gravitational forces are not able to provide a satisfactory explanation of galaxy formation in an expanding universe. The temperature gradients set up in the hot universe of Gold and Hoyle help in this process.

The resulting system, however, is not a single galaxy, but a supercluster of galaxies containing $\sim 10^3 - 10^4$ members. Such large-scale inhomogeneities in the distribu-

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tion of galaxies caution us against applying the cosmological principle too rigorously. For example, if we are in a particular supercluster, we expect to see a preponderance of galaxies of ages similar to that of ours in our neighbourhood out to say 20 or 30 Mpc. Thus it will not be surprising if our local sample yields an average age much larger than the universal average of $(3H_0)^{-1} \approx 3 \times 10^9 h_0^{-1}$ years. (Here H_0, the Hubble constant, is written as $H_0 = 100\, h_0$ km/s per Mpc, and current measurements give $h_0 \sim 0.7$.)

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Notice, however, the difference in approach here and the standard astroparticle physics. The latter relies on untested extrapolation of particle physics coupled with assumed initial conditions for seeding large-scale structure and seeks to arrive at the present hierarchy of structures through several regimes of evolution neither all directly observable, nor analytically calculable. The former process in the SSM on the other hand is based on beta-decay which is well tested in the laboratory. Moreover, it is happening on time scales of the order of the present day expansion, to arrive at the observed supercluster scale structure. (The crucial time scales, like 10^{-36} second, in modern astroparticle physics have no operational meaning.)

In the 1960s cosmologists by and large had not gone beyond classical gravity to address the problem of structure formation; nor had they gone to the extent of accepting structure on the scale of superclusters. The appeal to a particle-physics interaction in the above model was therefore viewed with skepticism, and its outcome in the form of superclusters considered irrelevant to cosmology.

The Gold–Hoyle hot universe model had continuous creation of neutrons. In general Hoyle believed that baryons (in preference to antibaryons) would be created. This breaks the baryon–number conservation law as well as baryon–antibaryon symmetry which were considered sacrosanct in the 1960s. Thus when our paper [9] on non-conservation of baryons in cosmology came up, the physicists who took note of it argued that the idea violated the above principle.

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Again it is significant that with the approach to Grand Unified Theories (GUT) particle physicists themselves found these principles no longer necessary. Indeed they were highly constraining to Big Bang cosmology if one wished to explain the observed baryon-antibaryon asymmetry and the baryon to photon ratio. Finally, high energy particle physicists have dropped these symmetries at very high energies.

On one occasion Fred Hoyle himself answered the criticism on baryon non-conservation by stating that this is the consequence of broken symmetry which perpetuates itself. The C-field which mediates in the creation process may have internal degrees of freedom that favour matter over antimatter. Since in later (post-1964) versions of the C-field, action at a distance formulation was used, one could argue that the information of broken symmetry in one spacetime event could be carried along light cones to the future and thus spread all over the universe.

It is somewhat ironical that today cosmologists uncritically accept concepts like GUTs and supersymmetry, phase transition at 10^{16} Gev, non-baryonic dark matter (cold or hot) as foundations to build the evolution of the universe across a decrease of 87 *orders of magnitude* in density and 29 orders of magnitude in temperature, when *none of the physics of the initial epochs is tested in a laboratory*. Compared to these leaps of beliefs, the assumptions of SSM were much less adventurous.

8. The Role of Superclusters in Radio-Source Counts

In 1961, Martin Ryle and his colleagues at the Mullard Radio Astronomy Observatory in Cambridge announced the results of the 4C radio source survey, claiming that the source counts had a super-Euclidean slope that disproved the steady-state theory. In a uniform distribution of sources in a Euclidean universe, the number N of sources brighter than flux density S goes as $S^{-1.5}$. That is, in the log N − log S plot the slope of the number count $N(> S)$ curve will be -1.5. Ryle reported a slope of -1.8, whereas the steady state theory was expected to give a slope beginning with -1.5 at high S, and flattening at lower values of S. In January of 1961, Ryle publicised this claim that the steady-state theory was disproved by his source count data.

I had joined as Hoyle's research student barely six months earlier and he asked me to develop a counter to Ryle's claim along the following lines:

1. Assume that the universe is inhomogeneous on the scale $\sim$ 50 Mpc of superclusters. Thus there will be more galaxies in a supercluster, and fewer (ideally zero) in the void outside it.

2. Assume that a galaxy becomes a radio source as it ages, i.e., the probability P that the galaxy becomes a radio source increases with age τ. He suggested an empirical formula $P \propto \exp(4H\tau)$.

The supercluster idea had come from the Gold–Hoyle hot universe model. The notion of age-dependence of radio source property was based on the then emerging indications that radio sources do not arise from colliding galaxies but are generally associated with elliptical galaxies (which were considered older than spirals). In any case Fred Hoyle had maintained a reasonable stand that one should not draw cosmological conclusions from populations of sources whose physics was still unknown. Even today the 'power-house' of a double radio source and the genesis of its jets are hardly well understood.

With these postulates, which in no way altered the basic tenets of the steady-state cosmology, we were able to demonstrate that an 'average' $\log N - \log S$ curve can have a super-Euclidean slope at high flux levels as found by Ryle, and his team [10].

The point that Hoyle wished to emphasize was that because of supercluster-scale inhomogeneity, the slope of the $\log N - \log S$ curve fluctuates at large values of S depending on the location of the observer, although at low S it settles down to the cosmological sub-Euclidean value predicted analytically. This expectation was later confirmed by deeper surveys.

To demonstrate this fluctuation, Fred Hoyle and I thought of carrying out N-body Monte-Carlo simulations on an electronic computer. The Cambridge EDSAC was manifestly inadequate for this computation, but Hoyle had access to an IBM 7090 in London, once a week. So with a few weekly visits to London, I was able to carry out this demonstration. *This was probably the first computer simulation in cosmology* [11].

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A great deal was made of the steepness of the $\log N - \log S$ curve at high flux end, with the claim that it implies evolution which is inconsistent with the steady-state cosmology. Kellermann and Wall have commented on how the effect was blown out of proportion, being confined to about 500 relatively nearby sources. Indeed if the result was cosmologically significant then one must demonstrate that the source population has evolved over the period covered by the survey. For testing evolution one needs to know the redshifts of these sources. Very few redshifts were known in 1961–62. By the mid-1980s, however, most sources in the 3CR catalogue[1] had their redshifts determined. Using this additional information DasGupta *et al* [12] were able to show that no evolution was necessary for the consistency of most Friedmann models[2] (with $\lambda = 0$), with the source count data as per the 3CR catalogue. DasGupta later also showed that even the steady-state cosmology was consistent with the 3CR source count.

[1] The surveys of radio sources by the Cambridge radio astronomers were labelled 1C, 2C, 3C, etc., to distinguish the first survey from the second one and so on. The 3CR is the revised version of the third Cambridge survey.

[2] In 1922–24, Alexander Friedmann was the first to look for non-static models of the universe as given by Einstein's equations of general relativity. These models are named after Friedmann and they served as the theoretical yardsticks against which to compare observations.

In the 1960s, the concept of superclusters was not 'standard' and most cosmologists believed that the universe was homogeneous on scales larger than clusters of galaxies ($\sim$ 5 Mpc). The idea that the universe can be inhomogeneous on the supercluster scale introduces a larger degree of fluctuations in the predicted values of observational tests of homogeneous cosmology. Evidence existed from the studies of George Abell, Gerard de Vaucouleurs and Shane and Wirtanen on superclusters but nobody believed that the universe could be inhomogeneous on such a large scale. The 'complication' introduced by us of inhomogeneity on the scale of suplerclusters ($\sim$ 50 Mpc) was therefore felt unnecessary in the opinion of many theoreticians and certainly a high price to pay in order to keep the steady-state theory alive. It was some two decades later, in the 1980s, that the existence of superclusters and voids on scales of 50–100 Mpc became part of standard cosmology.

9. Inflation and the Bubble Universe

I now come to the field theory with which Hoyle and I worked in order to derive the physical properties of the steady-state universe related to gravity and matter creation. As mentioned before, the C-field theory, as it is called, was in fact based on the scalar field formulation provided by M H L Pryce in 1961 as a private communication. It involved adding more terms to the standard relativistic Einstein–Hilbert action to represent the phenomenon of creation of matter. Using Occam's razor[3],

[3] Occam's razor is a phrase that indicates that the theory that requires fewer parameters to explain facts observed, is the better one. It is attributed to the 14th century English theologist William of Occam.

the additional field to be introduced was a scalar field with zero mass and zero charge.

Thus it is the negative energy density of the C-field that produces a repulsive gravitational effect. It is this repulsive force that drives the expansion of the universe. The strength of this effect is indicated by a coupling constant f that multiplies the C-field energy tensor. In the steady-state model as a solution of these equations, the density of matter is just this constant f.

The above effect may resolve one difficulty usually associated with the quantum theory of negative energy fields. Because such fields have no lowest energy state, they normally do not form stable systems. A cascade into lower and lower energy states would inevitably occur if we perturb the field in a given state of negative energy. However, this conclusion is altered if we include the feedback of repulsion on spacetime geometry through the negative energy. This feedback results in the expansion of space and in the lowering of the magnitude of field energy. These two effects tend to work in opposite directions and help stabilize the system.

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A first order perturbation of the modified field equations and of the steady-state solution also tells us that the solution is stable [13]. Indeed, a stability analysis brings out the key role played by the creation process. This tells us that the created particles have their world lines along the normals to the surfaces of constant C. Hoyle had argued that such a result gave a physical justification for the observed symmetry and regularity of the large-scale universe. We therefore argued that even if the universe was considerably different from the homogeneous and isotropic form in the remote past, the creation process would drive it to that state eventually. Years later this idea resurfaced in the context of inflation as the 'cosmic no hair conjecture', namely that an inflationary universe wipes out the initial irregularities and

Although the basic physics is different, the similarity between this model and the inflationary model that came into fashion 15 years later is obvious. In both models a phase transition creates the bubble which expands into the outer de Sitter spacetime.

leads to homogeneity and isotropy. It has been recognized by Barrow and Stein Schabes [14] that this notion is very similar to the above result derived by us in the early sixties.

However, as it turned out, Hoyle had anticipated the very idea of inflation in the mid-1960s. This was published in a paper with myself as co-author [15], where we discussed the effect of raising the coupling constant f by $\sim 10^{20}$. We would then have a steady-state universe of very large density ($\rho_0 \simeq 10^{-8}$g cm^{-3}) and very short time-scale ($H_0^{-1} \simeq 1$ year!). If in such a dense universe creation is switched off in a local region, that is, if we locally have a phase transition from the creative to the non-creative mode then this local region will expand according to the 'non-singular' analogue of the Einstein–de Sitter model of standard cosmology[4] (now more popularly known by the parameters $\Omega_{\text{matter}} = 1$, $\Omega_\Lambda = 0$) which has $S(t) \propto t^{2/3}$. Indeed, for small t_0, the solution rapidly approaches the Einstein–de Sitter form. Because of the domination by the negative energy term in the dynamical equation, the singularity at $S = 0$ is avoided. Being less dense than the surroundings, such a region will simulate an air bubble in water. Although the basic physics is different, the similarity between this model and the inflationary model that came into fashion 15 years later is obvious. In both models a phase transition creates the bubble which expands into the outer de Sitter spacetime. In the steady-state universe, such bubbles could arise in many places at different epochs from $t = -\infty$ to $t = +\infty$.

According to this model, this bubble is all that we see with our surveys of galaxies, quasars and so on. Hence our observations tell us more about this unsteady perturbation than about the ambient steady-state universe. There are, however, observable effects that give indications of the high value of f. For example, we showed that particle creation is enhanced near already

[4] Einstein and deSitter collaborated to produce the simplest model of an expanding universe as the solution of Einstein's equations. This model is named after them although Friedmann had arrived at that result seven years earlier, in 1924.

existing massive objects and that the resulting energy spectrum of the particles would simulate that of high-energy cosmic rays. The actual energy density of cosmic rays requires the high value of f chosen here.

In the mid-1960s the notion of a massive black hole at the nucleus of a galaxy had not received 'standard sanction' and so the idea remained relatively unknown, especially because it was proposed in the context of a steady-state universe.

10. Nuclei of Galaxies

The following extract from the abstract of the Hoyle–Narlikar paper [16] will indicate Hoyle's ideas in the mid-1960s on the dynamics of galaxy formation:

"... We suggest that the condensation of ... galaxies depends on the presence of inhomogeneities, in particular that a galaxy is formed around a central mass concentration. Because the Einstein-de Sitter expansion law is the limiting case between the expansion to infinity at finite velocity and a fall-back situation, in which the expansion stops at some minimum but finite density, a central condensation with mass appreciably less than that of the associated galaxy suffices to prevent continuing expansion. A mass of $10^9 M_\odot$*, for example, will restrain a total mass of* $\sim 10^{12} M_\odot$ *from expanding beyond normal galactic dimensions ..."*

In the mid-1960s the notion of a massive black hole at the nucleus of a galaxy had not received 'standard sanction' and so the idea remained relatively unknown, especially because it was proposed in the context of a steady-state universe. I briefly elaborate on the idea indicated in the above abstract, while stressing that the arguments were made in the mid-1960s.

The cosmological basis of this work was discussed in the preceding paper [15] which supposed that the universe, or a portion of it, expands from an initially steady-state situation with $\rho \simeq 10^{-8}\text{g cm}^{-3}, H^{-1} \simeq 10^{18}$ cm, that creation is effectively zero during this expansion, and that the Einstein–de Sitter expansion law holds in first approximation. The Newtonian analogue of the

Einstein–de Sitter law is given by

$$\dot{r}^2 = 2GM/r.$$

Next, consider the Newtonian problem of an object of mass μ placed at the origin $r = 0$, with all conditions for a particular element of the cloud being the same as before at a particular moment. Denote the value of r at this moment by r_0. Then $\dot{r}$ at this moment is $(2GM/r_0)^{1/2}$, as before, and the subsequent motion of the element in question is determined by

$$\dot{r} = \frac{2G(M+\mu)}{r} - \frac{2G\mu}{r_0}\,.$$

The outward velocity drops to zero, and the element subsequently falls back toward $r = 0$. The maximum radial distance $r_{\max}$ reached by the element is given by

$$r_{\max} = \{1 + (M/\mu)\}r_0,$$

and for sufficiently large M/μ, $r_{\max} \simeq Mr_0/\mu$, so that the fractional increase $r_{\max}/r_0$, above the radius r_0 at which the element had the same radial motion as in the Einstein–de Sitter case, is just M/μ. This factor is larger for elements more distant from μ than for the inner parts of the cloud; so the outer parts recede proportionately further than the inner parts.

What determines the particular moment at which the Einstein–de Sitter condition, $\dot{r} = (2GM/r)^{1/2}$, holds for any particular sample of material? To come to grips with this important question we must consider the relativistic formulation of the problem.

A complete solution of a local gravitational problem can be represented as a power series in the dimensionless parameter $2G(M + \mu)/r$, which must be $\ll 1$, this being what we mean by a 'local problem'. The Newtonian solution is of course the first term in this series. However, it is clear that we cannot use the Newtonian solution for the effect of μ if the second order term in $2GM/r$ exceeds the first order term in $2G\mu/r$, as is possible when $\mu/M \ll 1$. Hence the Newtonian equations for the effect of μ, cannot be used unless the moment for which we use $r \equiv r_0$, $\dot{r} = (2GM/r_0)^{1/2}$, is such that

$$\frac{2G\mu}{r_0} \geq \left(\frac{2GM}{r_0}\right)^2.$$

By taking the equality sign in the above relation, we do indeed define a particular value of r, corresponding to a specified M, namely,

$$r_0 = 2GM \times \left(\frac{M}{\mu}\right).$$

The situation is that the Newtonian calculation for the effect of μ can be applied to the subsequent motion of an element of material such that the specified M lies interior to it. But can we use $(2GM/r_0)^{\frac{1}{2}}$ as the starting velocity in this calculation? Not in general, because the cloud will generally have at least small fluctuations from the Einstein–de Sitter expansion. We shall confine ourselves here to the case in which the conditions $r \approx r_0$, $\dot{r} = (2GM/r_0)^{\frac{1}{2}}$, with r_0 given as above, hold for all M. Then

$$r_{\max} \simeq \frac{M}{\mu} r_0 \simeq 2GM\left(\frac{M}{\mu}\right)^2.$$

This result has a number of interesting consequences. Set $r_{\max}$ equal to a typical galactic radius, $r_{\max} = 3\times10^{22}$ cm. We then get

$$\frac{M}{M_\odot} \simeq 5 \times 10^5 \left(\frac{\mu}{M_\odot}\right)^{\frac{2}{3}}.$$

A central object of mass $\mu = 10^9 M_\odot$ gives $M = 5 \times 10^{11} M_\odot$, while $\mu = 10^7 M_\odot$ gives $M = 2 \times 10^{10} M_\odot$. It is of interest that the central condensations present in massive elliptical galaxies are known to be of order $10^9 M_\odot$ and that the total masses are believed to be $\sim 10^{12} M_\odot$.

This agrees with observation, in that no ultimate maximum radius has yet been found; the conventional radii are simply those set by the sensitivity of particular observing techniques.

Suppose that during expansion stars are formed from gas. The stars will continue to occupy the full volume corresponding to their maximum extension from the centre, so that the mass of the stars interior to r is given by

$$\frac{M(r)}{M_\odot} \simeq 2 \times 10^5 \left(\frac{\mu}{M_\odot}\right)^{\frac{2}{3}} r^{\frac{1}{3}},$$

where r is in kiloparsecs. Evidently, the mean star density at distance r from the centre is proportional to M/r^3, i.e., to $r^{-\frac{8}{3}}$. So long as the stars have everywhere the same luminosity function, the emissivity per unit volume at distance r is proportional to $r^{-\frac{8}{3}}$. This determines the light distribution in a spherical elliptical galaxy.

To obtain the projected intensity distribution we first note that the above considerations can be applied to values of r beyond normal galactic dimensions. There is no upper limit to r so long as we are dealing with a single condensation. This agrees with observation, in that no ultimate maximum radius has yet been found; the conventional radii are simply those set by the sensitivity of particular observing techniques. This being so, the intensity distribution $I(r)$ of the projected image is obtained by multiplying the volume emissivity by the factor r, and is $I(r) \propto r^{-\frac{5}{3}}$. This proportionality is slightly less steep than Hubble's luminosity law for $r \gg a$,

$$I(r) \propto (r/a + 1)^{-2} \approx r^{-2}.$$

The measurements for early ellipticals E1, E2, E3 give very good agreement with $r^{-\frac{5}{3}}$, better than with r^{-2}.

The $r^{-\frac{5}{3}}$ proportionality must not be used for too small r. The reason is simply that if M is set too small, the mean density corresponding to $M/(\frac{4}{3}\pi r_0^3) \propto M^{-5}$ becomes larger than the steady-state value of $\sim 10^{-8}\mathrm{g/cm}^3$ from which the expansion started. Instead, we then have an initial radius r_i given by

$$\frac{4}{3}\pi r_i^3 \rho_i = M, \quad \rho_i \simeq 10^{-8}\mathrm{g/cm}^3,$$

and

$$r_{\max} \simeq \frac{M}{\mu} r_i, \ \frac{M}{\mu} \gg 1.$$

Likewise, with r now in parsecs, we have

$$r \simeq 10^{-5}\frac{M}{\mu}\left(\frac{M}{M_\odot}\right)^{\frac{1}{3}}.$$

As an example, for $M = 10^{11}M_\odot$, $\mu = 10^8 M_\odot$, we get $r \simeq 30$ parsecs. This result is very satisfactory in that it predicts highly concentrated points of light at the centres of elliptical galaxies.

Note that in this scenario, the formation of a massive object in the centre of the galaxy is not discussed. In 1965–66, Hoyle and I assumed its existence and worked out consequences of the above type. The creation process is expected to generate more mass preferentially near an existing massive object, and so the mass grows to a large size, until the accumulation of the excess C-field leads to repulsive instabilities and explosive phenomena may occur. This process was discussed in detail in the book [17] by Hoyle, Burbidge and Narlikar.

This idea too did not get much attention by those interested in the cosmogony of galaxies, partly because the standard methods of gravitational contraction of gas clouds could not give such collapsed objects as endstates. Today, however, there is great enthusiasm regarding the existence of supermassive black holes in the nuclei of galaxies, both in terms of their theoretical consequences and observational features.

However, in the standard scenario, the formation of a supermassive object through gravitational collapse is still not properly understood – the reason being the same as that which led to the general scepticism of the concept in the 1960s. A major difficulty has been now to get rid of the angular momentum of the initial state from which collapse is supposed to ensue. Angular momentum of an isolated dynamical system is conserved. Thus we expect that a contracting object will spin faster and faster. This is not seen in practice.

11. Is the Universe Accelerating?

Recently, there has been considerable hype on the 'accelerating universe'. The source of this enthusiasm for the accelerating models is in the observations of redshifts z and apparent magnitudes m of distant (high redshift) supernovae. In the expanding universe model, the apparent magnitude can be related to the redshift through an explicit relation that depends on the model chosen, provided (i) the light source used (in this case the peak luminosity of the supernova) is truly a standard candle, and (ii) there is no intergalactic absorption enroute from the source to the observer.

In the 1960s and 1970s, Allan Sandage and his collaborators played an extensive role in applying this test to the expanding universe models. At the time, the invariable conclusion from such studies was that the universe is *decelerating*. Indeed, standard texts in cosmology usually define a *deceleration parameter* q_0 by

$$q_0 = -\frac{\ddot{S}}{S} \times H_0^{-2} ,$$

where H_0 is the present value of the Hubble constant. Sandage usually quoted values of this parameter ranging from 1 down to almost zero but positive. All Friedmann models then under discussion had $\lambda = 0$ and predicted positive q_0.

There was one joker in the pack, though! The steady-state model with $S \propto \exp(Ht)$, predicted $q_0 = -1$. It was singled out as an example of a wrong cosmology.

Today the situation is the other way round: the general consensus is that q_0 is negative. However, I am disappointed to see that none of the experimental groups associated with this result have even made a passing reference to the steady-state theory as giving the right value of q_0. The steady-state theory may be faulty on other counts, but surely it does deserve a pat on the back that it predicts an accelerating universe.

Why does the steady-state theory predict an accelerating universe? This is because it employes, in Fred Hoyle's approach, a *negative energy scalar field*, viz., the C-field. A negative energy field used in Einstein's equations, produces repulsion and hence acceleration. Today attempts are being made to put in dynamics behind the λ-term, with claims of quintessence or dark energy being already made with the firmness and confidence that remind us of Landau's cynical comment: *Cosmologists are always wrong but never in doubt.* A consensus will eventually develop that this effect is possible only under the regime of a negative energy field. But, again hardly anyone would bother to reference the work on C-field which precedes the present work by four decades.

Recently Narlikar *et al* [18] have argued that the quasi-steady state cosmology (which employes a *negative* cosmological constant) produces an $m - z$ relation[5] for supernovae that is fully consistent with observations including that of the high redshift supernova 1997 ff. Here the creation field used by the QSSC[6] behaves like a positive cosmological constant (as in the steady state theory); however, the main effect is produced by the intergalactic dust. It is significant that the magnitude of the dust density required for thermalizing starlight in order to generate the cosmic microwave background in the QSSC is fully consistent with the value obtained for a good fit of the theoretical $m - z$ curve to the observations.

[5] Relation between apparent brightness and cosmological epoch.

[6] QSSC stands for the quasi-steady state cosmology. The negative energy field repels matter and this makes the universe expand just as it would under the influence of a positive cosmological constant.

Intergalactic dust is another concept that Fred proposed in the 1970s in order to explain the cosmic microwave background as thermalized starlight. It was in the 1990s, within the framework of the QSSC that the idea found a workable framework [17] . For, it is not only possible to demonstrate that the starlight from stars of previous generations can be adequately thermalized by such dust, but one also gets the present day temperature of CMBR (Cosmic Microwave Background Radiation) as 2.7 K, a feat not yet achieved by standard cosmology. Further, as shown by Narlikar *et al* [19] one can also understand the angular power spectrum of inhomogeneities of the CMBR.

12. A General Comment

I have given these instances to counter the impression generally created that Hoyle was right about stellar evolution, nucleosynthesis, and molecular astronomy but mostly wrong about cosmology. His perception of large-scale inhomogeneity of the universe on the supercluster scale, the use of Monte Carlo N-body simulations in cosmology, his appreciation of a possible role that particle physics could play in cosmology, the bold assertion that the baryon number is not conserved, the anticipation of a model very similar to that of inflation, the inclusion of negative energy and negative stress fields in the dynamics of the universe and the notion that galaxies have compact massive nuclei controlling their dynamics and shapes were regarded as outlandish at the time they were proposed but became part of the mainstream cosmology, when proposed by others much later. It is unfortunate that later generations 'rediscovering' these ideas have either been ignorant of Fred Hoyle's earlier work or, if they were aware of it, they have chosen to ignore it.

It is unfortunate that later generations 'rediscovering' these ideas have either been ignorant of Fred Hoyle's earlier work or, if they were aware of it, they have chosen to ignore it.

The cartoons (*Figure* 4) illustrate three kinds of interaction an individual scientist may have vis-a-vis the

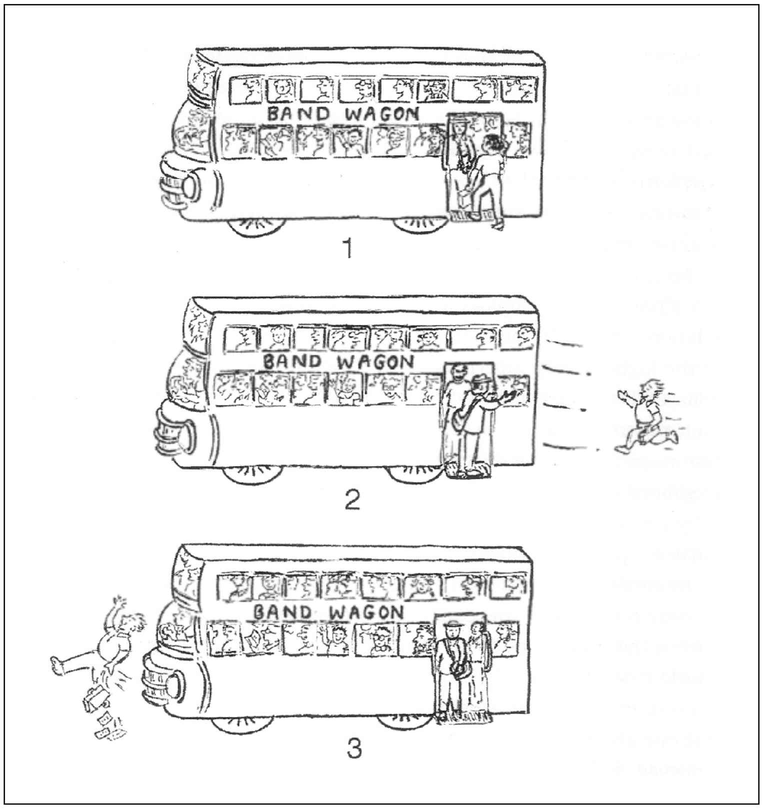

Figure 4.

mainstream research, representing a man catching a bus named (appropriately) the 'Bandwagon'. Cartoon (1) shows a typical bright young scientist who is wise enough to base his research on mainstream ideas, for that way lies progress, promotion and prosperity. He just ensures that he gets on the bus at the right time. Cartoon (2) represents a scientist who has thought of an idea too late, for it is already known to the community: he has rightly missed the bus. Cartoon (3) shows a scientist like Fred Hoyle who was years ahead of his times. The bandwagon follows him, but alas, far from giving him the credit for his ideas, knocks him out!

Acknowledgement: I thank Prof. Biman Nath, Editor of *Resonance* for encouraging me to write this tribute to Fred Hoyle. For the cartoons I am indebted to my wife Mangala.

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The man who voyages strange seas must of necessity be a little unsure of himself. It is the man with the flashy air of knowing everything, who is always with it, that we should beware of.

Fred Hoyle