DUNLOP, J. S. & PEACOCK, J. A. 1990. *MNRAS*, **247**, 19
EALES, S. A., RAWLINGS, S. 1996 *ApJ*, **460**, 68
FIXSEN, D. J., CHENG, E. S., GALES, J. M., MATHER, J. C., SHAFER, R. A. & WRIGHT, E. L. 1996 *ApJ*, **473**, 576
GOWER, J. F. R. 1966 *MNRAS*, **133**, 151
HOYLE, F. 1949 *MNRAS*, **109**, 365
1953 *ApJS*, **1**, 121
HOYLE, F. & TAYLER, R. J. 1964 *Nature*, **203**, 1108
INSKIP, K. J., BEST, P. N., LONGAIR, M. S. & MACKAY, D. J. C. 2002a *MNRAS*, **329**, 277
INSKIP, K. J., BEST, P. N., RÖTTGERING, H. J. A., RAWLINGS, S., COTTER, G. & LONGAIR, M. S. 2002b *MNRAS*, **337**, 1407
LEMAÎTRE, G. 1931 *Nature*, **127**, 706
LILLY, S. M. & LONGAIR, M. S. 1984 *MNRAS*, **211**, 833
LONGAIR, M. S. 1998 *Galaxy Formation* (Berlin: Springer-Verlag)
1995 'Astrophysics and Cosmology' in *Twentieth Century Physics*, eds. L. M. Brown, A. Pais and A. B. Pippard, 3, 1671 (Bristol: IOP Publishing and Philadelphia New York: AIP Press)
MCCARTHY, P. J., VAN BREUGEL, W. J. M., SPINRAD, H. & DJORGOVSKI, S. 1987 *ApJ*, **321**, L29
METCALFE, N., SHANKS, T., CAMPOS, A., FONG, R. & GARDNER, J. P. 1996 *Nature*, **383**, 236
MILLS, B. & SLEE, O. B. 1957 *Aust. J. Phys.*, **10**, 162
PEACOCK, J. A., COLE, S., NORBERG, P. *et al.* 2001 *Nature*, **410**, 169
RYLE, M. 1955 *Observatory*, **75**, 137
SCHEUER, P. A. G. 1957 *Proc. Camb. Phil. Soc.*, **53**, 764
1974 *MNRAS*, **167**, 329
1975 in *Stars and Stellar Systems, vol. 9 of Galaxies and the Universe*, eds. A. R. Sandage, M. Sandage and J. Kristian (Chicago: University of Chicago Press)
SHAKESHAFT, J. R., RYLE, M., BALDWIN, J. E., ELSMORE, B. & THOMSON, J. H., 1955 *Mem. RAS*, **67**, 106
SULLIVAN, W. T. III 1984 *The Early Years of Radio Astronomy* (Cambridge: Cambridge University Press)
WAGONER, R. V., FOWLER, W. A. & HOYLE, F. 1967 *ApJ*, **148**, 3
WALL, J. V. 1996 in *Extragalactic Radio Sources*, IAU Symposium No. 175, eds. R. Ekers, C. Fanti and L. Padrielli (Dordrecht: Kluwer Academic Publishers) p. 547

9

Alternative ideas in cosmology

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It is shown that in cosmology, as in the rest of science, the evolution of observational evidence and theoretical concepts has often led to the acceptance of ideas that were once considered outlandish. Fred Hoyle himself was responsible for generating several such ideas, although he was much ahead of his time. Here some of those ideas are outlined, ideas that were thought to be unrealistic at the time they were proposed, but which have now been assimilated into mainstream cosmology. A general comment that emerges from such examples is that highly creative individuals who are far ahead of their time do not get the recognition they deserve once their ideas are accepted as standard.

9.1 Introduction

The original title suggested for my contribution to the meeting dedicated to the memory of Fred Hoyle had been 'Alternative cosmologies'. I changed it to the present title for the following reason. There have been occasional reviews of alternative cosmologies from time to time, the most recent one being by myself and Padmanabhan (2001). Fred himself had been the originator of a few alternative cosmologies. However, in the present context, while highlighting his contributions to cosmology it is more interesting to look at ideas *on specific topics* of cosmological interest rather than at cosmological models per se.

In the decade following the observations of the microwave background radiation by Penzias and Wilson (1965), most cosmologists made up their minds that the so-called Big-Bang cosmology provides the correct framework in which

The Scientific Legacy of Fred Hoyle, ed. D. Gough.

to describe the history and large-scale structure of the Universe. Although there existed a range of possible models within this framework, they become collectively known as 'standard cosmology'. Any other cosmological model that did not fall within the standard framework was identified as 'non-standard cosmology'. A review entitled 'Non-standard cosmologies' by myself and Kembhavi (1979) summarized how such models dealt with the various theoretical concepts in cosmology and the available observational data.

However, in the 1980s the adjective 'non-standard' (which has somewhat negative connotations) was replaced by 'alternative', it being presumed that the alternative was with respect to standard cosmology.

Nevertheless, the adjective 'standard' is itself a misnomer, since it implies something stable and invariant with respect to which others can be measured. (The dictionary meaning of 'standard' is typically 'of recognized authority or prevalence'.) In a highly critical article on cosmology Disney (2000) has given reasons as to why this adjective is inappropriate in the sense in which it is used in the context of cosmology. Indeed, he has argued that the standard model in cosmology is nowhere as secure and laboratory-tested as the standard model in particle physics.

That the standard cosmology has evolved considerably in the four decades since the 1960s is seen from the various new concepts it has acquired during that period, namely, inflation, dark matter, non-baryonic matter, cosmological constant or quintessence or dark energy, new physics involving more than four dimensions, etc. Indeed, ideas that were once considered 'non-standard' have now become acceptable as 'standard'.

It makes sense therefore to concentrate here on such alternative ideas in cosmology, particularly those with whose origin Fred Hoyle was associated. As I propose to show, these ideas were not accepted at the time they were proposed, but gradually found their way into the 'standard' category as cosmology evolved. Before proceeding further, however, it is instructive to take a brief look at the historical evolution of cosmological ideas from earlier times.

9.2 From Aristarchus to Hubble

For viewing history one may define 'standard' at any epoch as representing ideas believed by the majority at that epoch, while 'alternative' would stand for ideas significantly different from the standard one (prevailing at the time) but believed by a minority. As will shortly be seen, this distinction between 'standard' and 'alternative' is epoch-dependent. An idea falling within the alternative basket at epoch t might well be transferred to the standard basket at a later epoch $t + \Delta(\Delta > 0)$. Naturally, if $\Delta \gg$ human life-span, then we have to conclude that the originator(s) of the alternative idea(s) failed to get credit for them while still alive.

Take Aristarchus (*c.* 310–230 BC), for example, who argued that the Earth not only spins about its axis, but it also goes around the Sun. To prove his point, he proposed what is today known as the *parallax method* for measuring distances of nearby stars. The test failed not because the underlying hypothesis was false but because the stellar distances were underestimated and the observational techniques were not sensitive enough to measure the actual parallax.

The standard cosmology of those times firmly believed a geocentric universe. That belief remained intact till Copernicus (AD 1473–1543) appeared on the scene. However, it took nearly a century before his alternative idea of the heliocentric cosmology became accepted. Thus for Copernicus, $\Delta \cong 100$ yr. So far as Aristarchus is concerned, his contribution has been belatedly recognized relatively recently. His bust in his home-town of Samos carries the inscription:

> Aristarchus of Samos ... 320–230 BC ... First to discover the Earth revolves around the Sun ... Copernicus copied Aristarchus 1530 AD ...

Shall we say that Δ(Aristarchus) $\cong$ 23 centuries?

While the heliocentric theory became standard, it too had its factual limitations. By the beginning of the twentieth century, Herschel's picture of the Sun close to the centre of the Galaxy had become standard, and was adopted by J. C. Kapteyn in what had become known as the 'Kapteyn universe'. Harlow Shapley's measurements of distributions and distances of globular clusters, however, led to the realization that the Sun must be well away (~8–10 kpc) from the Galactic Centre. In this case one may set Δ at ~10 years, and Shapley could get the credit during his lifetime.

An alternative idea that roused considerable passion and controversy began with Immanuel Kant (1724–1804), and is known as Kant's 'island universe' hypothesis. This hypothesis envisaged the Universe as a limitless system, like a vast ocean, in which galaxies like our Milky Way existed like islands. Observations had indeed revealed a number of nebulae, cloud-like faint but luminous systems, some of which (like the Andromeda Nebula) were claimed by a small minority to be distant galaxies, the Kantian islands. The standard view to which even Shapley subscribed was, however, that *everything* observed till that date was part of our Milky Way, which was envisaged as the Great Galaxy. The above alternative claim was dismissed as unfactual. See, for example, the following extract from the popular 1905 book called *The System of the Stars* by Agnes Clerke:

> The question whether nebulae are external galaxies hardly any longer needs discussion. It has been answered by the progress of research. No competent thinker, with the whole of the available evidence before him, can now, it is safe to say, maintain any single nebula to be a star system of co-ordinate rank with the Milky Way...

The note of finality and certainty indicates the confidence felt by the majority in the correctness of the standard picture. Within two decades, however, this view had to be abandoned in the face of growing evidence against it and the lack of data in its favour. Let us first look at the latter.

The more accurate method of measuring the distances using the period–luminosity relation for the Cepheids, which had been introduced earlier, was applied by Hubble (1926) to M31 and M33. He found 50 variables in M31, of which 40 were cepheids, and 35 cepheids in M33. In addition, there were known to be nine in NGC6822, and Shapley had measured 105 in the Small Magellanic Cloud (SMC).

Of course, Hubble realized and stressed that these distances would be affected by any change in the zero point of the period–luminosity relation as it had been derived by Shapley. Still, the very large distances derived for the spirals were compatible with many attempts to determine the proper motion of the spirals, which had always led to null results (a velocity of 1000 km s^{-1} transverse to the line of sight would correspond to an annual proper motion of the order of $0''.0007$, a value far below what could be measured).

However, there was a stumbling block which led many to question these large distances. This arose from the claims by A. van Maanen (1916–30) at Mount Wilson to have determined proper motions *in the spiral arms* of a number of nearby spiral galaxies including M33, M81, M101, NGC2403, 4051, 4736, 5055, and 5195. At an indicative distance of 10^6 light years an annual motion $\sim 0''.01$, which was of the order of what was being claimed, corresponds to a velocity of $\sim$15 000 km s^{-1}. Thus van Maanen's results corresponded to periods of rotation of the spirals, if they were assumed to have sizes similar to the Milky Way, of the order 10^7 years or less, implying ejection of matter on similar timescales, so that the spirals would disintegrate in times of this order. However, later observations could not confirm these claims, and they gradually faded away.

Side by side with the lack of confirmation of proper motions, the new method of measuring distances using the Cepheid variables led Hubble to the conclusion that nebulae like the Andromeda Nebula (M31), M33, and several others lie well beyond the Galaxy. And so the Kantian island universe hypothesis began to gain credibility. If we date this change of paradigm to have taken place in the mid 1920s, then Δ(Kant) $\cong$ 1.5 centuries.

The above historical background may be kept in mind while evaluating the cosmological contributions of Fred Hoyle.

9.3 Interaction of particle physics with cosmology

It is generally assumed that particle physicists and cosmologists first got together in the 1980s, the latter using ideas from particle physics at very high energy in order to address issues like the origin and evolution of large-scale structure. 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 Symposium on Radio Astronomy. The 'hot universe' of Gold and Hoyle (1959) was the outcome. Briefly, the idea was as follows.

In the 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, as we shall see later, 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.

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

$$n \rightarrow p + e^- + \bar{\nu}. \tag{9.1}$$

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 $\geq$ 50 Mpc. It was already known that pure gravitational forces are not able to provide a satisfactory picture 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 distribution 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.

Although newly created electrons have a kinetic temperature of $\sim 10^9$ K, the temperature tends to drop because of expansion. The average temperature is three-fifths of this value, that is, around 6×10^8 K. It was suggested by Hoyle in 1963 that such a hot intergalactic medium would generate the observed X-ray background. However, quantitative estimates by R. J. Gould soon showed that the expected X-ray background in the hot universe would be considerably higher than what is actually observed, thus making the hot universe untenable. The present-day background measurements, however, do not rule out such a hot universe for $h_0 \approx 0.5$. Astrophysicists today are, however, inclined to look for other explanations for the origin of the X-ray background.

Although it is now discredited, the hot universe model was the first exercise in linking particle physics (neutron decay) to the formation of large-scale structures in the Universe.

Notice, however, the difference in approach here from 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 takes the process of beta decay, which is well tested in the laboratory and builds on it in timescales of the order of the present-day expansion, to arrive at the supercluster scale structure.

In the 1960s cosmologists by-and-large had not gone beyond classical gravity to address the problem of structure formation; nor had they (as seen in the following section) 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 scepticism, and the outcome in the form of superclusters was considered irrelevant to cosmology.

It is somewhat ironical that today cosmologists accept uncritically concepts like GUTs and supersymmetry, a phase transition at 10^{16} GeV, non-baryonic dark matter (cold or hot) as foundations on which 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*. Moreover, superclusters are no longer under a taboo, but are well accepted. Thus in this case, we have $\Delta \cong 20$ years for Fred.

9.4 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 stated these points to claim that the Steady-State theory was disproved.

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

(a) Assume that the Universe is inhomogeneous on the scale ~50 Mpc of superclusters. Thus there will be more galaxies in a supercluster, and fewer (ideally zero) in the void outside it.
(b) 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 a radio source property was based on the then-available 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 the 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 will have a super-Euclidean slope at high flux levels as found by Ryle *et al.* (Hoyle and Narlikar 1961).

The point that Fred 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 observationally by deeper surveys (Kellermann and Wall 1987).

To demonstrate this fluctuation, Fred 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 Fred had access once a week to an IBM 7090 in London. 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 (Hoyle and Narlikar 1962).

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 (1987) 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 1961–2. By the mid 1980s, however, most sources in the 3CR catalogue had their redshifts determined. Using this additional information DasGupta *et al.* (1988) were able to show that no evolution was necessary for the consistency of most Friedmann models (with $\Lambda = 0$), with the source-count data as per the 3CR catalogue. DasGupta (1988) later showed also that even the Steady-State cosmology was consistent with the 3CR source count. Similar complete redshift data for the 4C survey are not yet available for carrying out such analysis.

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 (~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 Abell (1958), de Vaucouleurs (1961), Shane and Wirtanen (1954) on superclusters, but nobody believed that the Universe could be inhomogeneous on such a large scale. The 'complication' introduced by inhomogeneity on the scale of superclusters (~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. Thus in this instance, I would set $\Delta \cong 25$ years for Hoyle's belief in superclusters.

I now return to the interaction between cosmology and particle physics.

9.5 Non-conservation of baryons and negative stress energy

I understand that Fred had sent his first manuscript on the Steady-State cosmology to a well known physics journal. It was rejected there presumably because physicists looked upon continuous creation as a violation of the law of conservation of matter and energy. (The reason for rejection cited by the journal, however, was a curious one, namely that it was facing shortage of paper.) He subsequently sent it to the astronomy journal *MNRAS*. In fact, unlike the version of Bondi and Gold (1948), the version of Steady-State cosmology advocated by Fred Hoyle (1948) *does not* violate the above conservation law. There, a scalar field of negative energy and pressure was used, an idea that physicists found abhorrent. It is significant that the idea is now gaining popularity, see its recent 'rediscovery' by Steinhardt and Turok (2002). Thus one could argue that $\Delta \cong 50$ years for this idea originally proposed by Hoyle.

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 (Hoyle and Narlikar 1966a) on non-conservation of baryons in cosmology came up the physicists who took note of it argued that the idea violated the above principles.

Again it is significant that with the approach to Grand Unified Theories 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. In the end, high-energy particle physicists have dropped these symmetries.

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 (see Hoyle and Narlikar 1964), 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.

If we date the notion of baryon non-conservation in cosmology to the Hoyle–Narlikar paper of 1966, and look at the 1979 publication by Steven Weinberg (entitled 'Baryon-lepton non-conserving processes'), we may set $\Delta = 13$ years for this idea. In fact all three of the trilogy of papers published by Hoyle and me in 1966 have found echoes in subsequent years as we shall see in the following two sections.

9.6 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. 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.

Like Hoyle's original approach, the C-field theory also involved adding more terms to the standard relativistic Einstein–Hilbert action to represent the phenomenon of creation of matter. Using Occam's razor, the additional field to be introduced was a scalar field with zero mass and zero charge. We denote this field by C and its derivative with respect to the spacetime coordinate x^i by C_i. The action is then given by (with c = speed of light),

$$\mathcal{A} = \frac{c^3}{16\pi G}\int R\sqrt{-g}\,d^4x - \Sigma_a m_a c\int ds_a - \frac{1}{2c}f\int C_i C^i\sqrt{-g}\,d^4x - \Sigma_a\int C_i da^i. \tag{9.2}$$

The additional terms (third and fourth) on the right-hand side are the C-field terms. Note that the last term of (9.2) is path-independent. If we consider the world line of particle a between the end points A_1 and A_2, we have

$$\int_{A_1}^{A_2} C_i\,da^i = C(A_2) - C(A_1). \tag{9.3}$$

Normally such path-independent terms do not contribute to any physics derivable from the action principle. So why include such a term? The answer to this question lies in the notion of 'broken' world lines. A theory that discusses creation (or annihilation) of matter per se must have world lines with finite beginnings or ends (or both). The C-field interaction term picks out precisely these end points of particle world lines. If we vary the world lines of a and consider the change in the action $\mathcal{A}$ in a volume containing the point A_1 where the world line begins, we get at A_1 (which is now varied)

$$m_a c\frac{da^i}{ds_a}g_{ik} - C_k = 0. \tag{9.4}$$

This relation tells us that *overall energy and momentum are conserved at the point of creation*. The 4-momentum of the created particle is compensated by the 4-momentum of the C-field. Clearly, to achieve this balance the C-field must have negative energy. We shall return to this point later. We also note that, since the interaction term is path-independent, the equation of motion of a is still that of a geodesic. The Pryce formulation is therefore a masterly way of dealing with creation (and annihilation) of matter without violating the conservation laws.

The constant f in the action (9.2) is a coupling constant. The variation of C gives the source equation in the form

$$C^k_{;k} = cf^{-1}\bar{n}, \tag{9.5}$$

where $\bar{n}$ is the number of net creation events per unit proper 4-volume.

Finally, the variation of g_{ik} leads to the modified Einstein field equations

$$R^{ik} - \frac{1}{2}g^{ik}R = -\frac{8\pi G}{c^4}\left(T^{ik}_{(m)} + T^{ik}_{(C)}\right), \tag{9.6}$$

where $T^{ik}_{(m)}$ is the matter tensor while

$$T^{ik}_{(C)} = -f\left(C^i C^k - \frac{1}{2}g^{ik}C^l C_l\right). \tag{9.7}$$

Again we note that $T^{00}_{(C)} < 0$ for $f > 0$. Thus the C-field has a negative energy density that produces a repulsive gravitational effect. It is this repulsive force that drives the expansion of the Universe. 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 cascading 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 (9.7) on spacetime geometry through (9.6). 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.

Using the Robertson–Walker line element and the assumption that a typical particle created by the C-field has mass m, we get the following equations out of the above set:

$$\dot{C} = mc^2, \tag{9.8}$$

$$mf\left(\ddot{C} + 3\frac{\dot{S}}{S}\dot{C}\right) = \left(\dot{\rho} + \frac{\dot{S}}{S}\rho\right)c^2, \tag{9.9}$$

$$2\frac{\ddot{S}}{S} + \frac{\dot{S}+kc^2}{S^2} = \frac{4\pi Gf}{c^4}\dot{C}^2, \tag{9.10}$$

$$3\frac{\dot{S}^2+kc^2}{S^2} = 8\pi G\left(\rho - \frac{f}{2C^4}\dot{C}^2\right). \tag{9.11}$$

It is easy to verify that the steady-state solution follows from these equations for

$$k = 0, \qquad S = e^{H_0 t}, \qquad \rho = \rho_0 = \frac{3H_0^2}{4\pi G} = fm^2. \tag{9.12}$$

Notice that both H_0 and ρ_0 are given in terms of the elementary creation process: that is, in terms of the coupling constant f and the mass of the particle created. Thus the Hoyle approach provides the quantitative information lacking in the deductive approach via the Perfect Cosmological Principle of Bondi and Gold.

A first-order perturbation of the above equations and of the steady-state solution also tells us that the solution is stable. 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 C = constant. Hoyle has argued that such a result gives a physical justification for the Weyl postulate; it tells us *why* the world lines of the fundamental observers are orthogonal to a special family of spacelike hypersurfaces. In the C-field cosmology these hypersurfaces are not just abstract notions but are seen to have a physical basis. 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 leads to homogeneity and isotropy. It has been recognized by Barrow and Stein Schabes (1984) that this notion is very similar to the above result derived by us in the early sixties (Hoyle and Narlikar 1963; $\Delta = 21$ years!).

However, as it turned out, Fred had anticipated the very idea of inflation in the mid 1960s. This was published in a paper with myself as coauthor (Hoyle and Narlikar 1966b) where we discussed the effect of raising the coupling constant f by $\sim 10^{20}$. As the formulae (9.12) show, we would then have a Steady-State universe of very large density ($\rho_0 \simeq 10^{-8}$ g cm^{-3}) and very short timescale ($H_0^{-1} \simeq$ 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:

$$C^i_{;i} = 0, \tag{9.13}$$

then this local region will expand according to the formula

$$S(t) \propto \left[1 + \frac{(t + t_1)^2}{t_0^2}\right]^{1/3}, \tag{9.14}$$

where t_1 and t_0 are constants. Note that this is the 'non-singular' analogue of the Einstein–de Sitter model of standard cosmology (now more popularly known by the parameters $\Omega_{\rm matter} = 1, \Omega_\Lambda = 0$), which has $S(t) \propto t^{2/3}$. Indeed, for small t_0, the solution rapidly approaches the Einstein–de Sitter form. 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 that 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 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.

Thus taking Fred's anticipation of inflation in 1966, we may set $\Delta = 15$ years.

9.7 Nuclei of galaxies

The following extract from the abstract of the Hoyle and Narlikar (1966c) paper will indicate Fred'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 that the above abstract indicates, while stressing that the arguments were made in the mid 1960s.

The cosmological basis of this work was discussed in the preceding paper (Hoyle and Narlikar 1966b), which supposed that the Universe, or a portion of it, expands from an initially steady-state situation with $\rho \simeq 10^{-8}$ 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

$$\dot{r}^2 = 2GM/r, \tag{9.15}$$

in which r is the radial coordinate of an element of material defined by the condition that in a spherically symmetric situation about $r = 0$, the mass interior to r is M. For a given sample of material M remains constant and $\dot{r} \to 0$ only as $r \to \infty$. Equation (9.15) is an integral of the second-order Newtonian equations, and the fact that no constant of integration appears represents the analogue of the Einstein–de Sitter law.

Next, consider the Newtonian problem of an object of mass μ placed at the origin $r = 0$, all conditions at a particular moment for a particular element of the cloud being the same as before. 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

$$\dot{r} = \frac{2G(M+\mu)}{r} - \frac{2G\mu}{r_0}. \tag{9.16}$$

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

$$r_{max} = \{1 + (M/\mu)\}r_0, \tag{9.17}$$

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, namely equations (9.16) and (9.17), cannot be used unless the moment for which we use $r \equiv r_0$, $\dot{r} = (2GM/r_0)^{1/2}$, is such that

$$\frac{2G\mu}{r_0} \geq \left(\frac{2GM}{r_0}\right)^2. \tag{9.18}$$

By taking equality in (9.18) we do indeed define a particular value of r, corresponding to a specified M, namely,

$$r_0 = 2GM \times \left(\frac{M}{\mu}\right). \tag{9.19}$$

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 in general the cloud will 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 by equation (9.19), hold for all M.

From equations (9.17) and (9.19) we have

$$r_{max} \simeq \frac{M}{\mu}r_0 \simeq 2GM\left(\frac{M}{\mu}\right)^2. \tag{9.20}$$

This result has a number of interesting consequences. Set r_{max} equal to a typical galactic radius $r_{max} = 3 \times 10^{22}$ cm. Then equation (9.20) leads to

$$\frac{M}{M_\odot} \simeq 5 \times 10^5 \left(\frac{\mu}{M_\odot}\right)^{\frac{2}{3}}, \tag{9.21}$$

where $M_\odot$ is the solar mass. 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 $\sim 10^{12}\,M_\odot$.

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 setting $r_{max} = r$ in equation (9.21). Numerically, we have

$$\frac{M(r)}{M_\odot} \simeq 2 \times 10^5 \left(\frac{\mu}{M_\odot}\right)^{\frac{2}{3}} r^{\frac{1}{3}}, \tag{9.22}$$

in which 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 $I(r) \propto r^{\frac{3}{2}}$. This proportionality is slightly less steep than Hubble's law for $r \gg a$:

$$I(r) \propto (r/a + 1)^{-2} \approx r^{-2}. \tag{9.23}$$

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

The $r^{-\frac{3}{2}}$ proportionality must not be used for too-small r, because r_0 given by equation (9.19) becomes invalid as M is reduced towards μ. The reason is simply that if M is set too small the mean density corresponding to equation (9.19), namely $M/\frac{4}{3}\pi r_0^3 \propto M^{-5}$, becomes larger than the steady-state value of $\sim 10^{-8}\,\mathrm{g\,cm^{-3}}$ from which the expansion started. Instead of equation (9.19), we then have an initial radius r_i given by

$$\frac{4}{3}\pi r_i^3 \rho_i = M, \qquad \rho_i \simeq 10^{-8}\,\mathrm{g\,cm^{-3}}, \tag{9.24}$$

and instead of equation (9.20),

$$r_{\max} \simeq \frac{M}{\mu} r_i, \qquad \frac{M}{\mu} \gg 1. \tag{9.25}$$

In place of equation (9.22) we have

$$r \simeq 10^{-5} \frac{M}{\mu} \left(\frac{M}{\mathrm{M_\odot}}\right)^{\frac{1}{3}}, \tag{9.26}$$

with r now in parsecs. As an example, for $M = 10^{11}\,\mathrm{M_\odot}$, $\mu = 10^8\,\mathrm{M_\odot}$, equation (9.26) gives $r \simeq 30$ parsecs. This result is very satisfactory in that it predicts a highly concentrated point 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 1965–6, Fred 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 by Hoyle, Burbidge and Narlikar (2000).

This idea too was not paid much attention to 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 a great enthusiasm for the existence of supermassive black holes in the nuclei of galaxies, both in terms of their theoretical consequences and the observational features. Thus again we find Fred ahead of the pack by $\Delta \cong 20$ years.

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 is how to get rid of the angular momentum of the initial state from which collapse is supposed to ensue.

Observation does not show the presence of massive black holes in the *discs* of spiral galaxies. Molecular clouds with masses upwards of $10^5\,\mathrm{M_\odot}$ are found, but only with average matter densities of $\sim 10^{-21}\,\mathrm{g\,cm^{-3}}$. The reason why there is no continuing condensation of such clouds is usually put down to rotary forces. When a cloud condenses, the inward gravitational forces increase as the inverse square of the scale of the cloud. But the rotary forces inhibiting condensation increase as the cube. Since the two are not far from being in balance initially, not much condensation is permitted before rotation becomes inimical to any further rise of the internal density.

The internal density inside a black hole of mass $10^6\,\mathrm{M_\odot}$, say, is about $10^4\,\mathrm{g\,cm^{-3}}$. So a molecular cloud of initial average density $10{-}21\,\mathrm{g\,cm^{-3}}$ would have to condense by upwards of a factor 10^8 in scale to produce a black hole, with rotary forces increasing by the immense factor of $\sim 10^{25}$. No amount of optimistic thinking can cope with an increase of that order. So what now is special about the centre of a galaxy, instead of the disc, to permit a rise of rotary forces by this same enormous factor? Nothing. The centre of a galaxy is certainly a unique point geometrically. But rotary forces are not suspended there. The situation is just the same there as for the discs of spirals. The alternative picture involving creation of matter described above does not have this problem.

9.8 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 en route 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

$$q_0 = -\frac{\ddot{S}}{S} H_0^{-2}, \tag{9.27}$$

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 made a reference to the Steady-State theory as giving the right value of q_0. The Steady-State theory may be faulted on other counts, but surely it does deserve a pat on the back for its prediction of an accelerating universe.

Why does the Steady-State theory predict an accelerating universe? This is because it employs, in Fred Hoyle's approach, a *negative-energy scalar field*, namely, the C-field. A negative-energy field used in Einstein's equations produces repulsion, and hence acceleration. Today, attempts are being made to put dynamics behind the Λ-term, with claims of quintessence or dark energy being already made with the same degree of firmness and confidence as was found in the Agnes Clerke quotation in Section 9.2. As is apparent from the work of Steinhardt and Turok (2002), 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 the C-field which precedes the present work by four decades.

However, let me return to the two provisos mentioned at the beginning of this section. Are we sure that we are dealing with standard candles? Recall that much of the work in the 1960s and 1970s involving galaxies as standard candles was vitiated by the possibility that there might be luminosity evolution in galaxies. How sure are we that a supernova at $z = 1.6$ has the same peak luminosity as a present-day supernova? A second element of uncertainty introduced

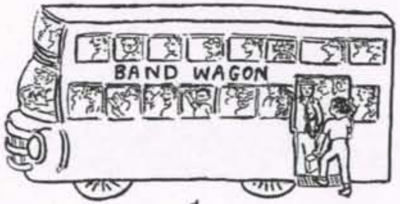
recently with regard to high redshift supernovae comes from gravitational lensing (Moertsell *et al.* 2001). At high redshift there is greater chance of a supernova being gravitationally lensed in such a way as to amplify its luminosity. The second proviso has been highlighted by Aguirre (1999), Banerjee *et al.* (2000) and Narlikar *et al.* (2002a), by pointing out that intergalactic dust can produce extra dimming of distant supernovae and thus apparently simulate the effect of a positive cosmological constant.

Recently Narlikar *et al.* (2002a) have argued that the quasi-steady-state cosmology (QSSC) (which employs a *negative* cosmological constant) produces an m–z relation for supernovae that is fully consistent with observations including that of the high-redshift supernova 1997ff. Here the creation field used by the QSSC 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 radiation (CMBR) in the QSSC is fully consistent with the value obtained for a good fit of the theoretical m–z curve to the observations.

Intergalactic dust is another concept that Fred proposed back in the 1970s in order to explain the CMBR as thermalized starlight. It was in the 1990s, within the framework of the QSSC, that the idea found a workable framework (Hoyle *et al.* 2000). 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 as 2.7 K, a feat not yet achieved by standard cosmology. Further, as shown by Narlikar *et al.* (2002b), one can also understand the angular power spectrum of inhomogeneities of the CMBR.

9.9 A general comment

I have given these instances to counter the impression generally created that Fred 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–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



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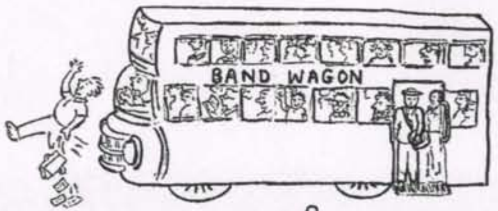

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proposed, but became part of mainstream cosmology when proposed by others much later.

It is unfortunate that later generations 'rediscovering' these ideas have either been ignorant of Fred's earlier work or have been aware of it but have chosen to ignore it. Examples of the former are to be found in the papers by Guth (1981) and Linde (1987), and of the latter in the recent work of Steinhardt and Turok (2002).

The cartoons (1)–(3) illustrate three kinds of interaction an individual scientist may have vis-à-vis 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 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!

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References

ABELL, G. O. 1958 *ApJS*, **3**, 211
AGUIRRE, A. N. 1999 *ApJ*, **512**, L19
BANERJEE, S. K., NARLIKAR, J. V., WICKRAMASINGHE, N. C., HOYLE, F. & BURBIDGE, G. 2000 *AJ*, **119**, 2583
BARROW, J. D. & STEIN SCHABES, J. 1984 *Phys. Lett.*, **103A**, 315
BONDI, H. & GOLD, T. 1948 *MNRAS*, **108**, 252
CLERKE, A. 1905 *The System of the Stars* (London: Adam & Charles Black) p. 349
DASGUPTA, P. 1988 Ph.D. Thesis, Bombay University
DASGUPTA, P., NARLIKAR, J. V. & BURBIDGE, G. 1988 *AJ*, **95**, 5
DISNEY, M. 2000 *GRG Journal*, **32**, 1125
GOLD, T. & HOYLE, F. 1959 *Proceedings of the Paris Symposium on Radio Astronomy*, ed. R. N. Bracewell (Stanford: Stanford University Press) p. 583
GUTH, A. 1981 *Phys. Rev.* D, **23**, 347
HOYLE, F. 1948 *MNRAS*, **108**, 372
HOYLE, F. & NARLIKAR, J. V. 1961 *MNRAS*, **123**, 133
1962 *MNRAS*, **125**, 13
1963 *Proc. Roy. Soc.* A, **273**, 1
1964 *Proc. Roy. Soc.* A, **282**, 178
1966a *Proc. Roy. Soc.* A, **290**, 143
1966b *Proc. Roy. Soc.* A, **290**, 162
1966c *Proc. Roy. Soc.* A, **290**, 177
HOYLE, F., BURBIDGE, G. & NARLIKAR, J. V. 2000 *A Different Approach to Cosmology* (Cambridge: Cambridge University Press)
HUBBLE, E. P. 1926 *ApJ*, **63**, 236
KELLERMANN, K. & WALL, J. V. 1987 *Proceedings IAU Symposium No. 124*, eds. A. Hewitt, G. Burbidge & L.-Z. Fang (Dordrecht: Reidel) p. 545
LINDE, A. 1987 *Physica Scripta*, **T15**, 169
VAN MAANEN, A. 1916–30 *Mt Wilson Contr.*, Nos. 111, 136, 158, 182, 204, 237, 270, 290, 321, 356, 391, 405–408
MOERTSELL, E., GUNNARSSON, C. & GOOBAR, A. 2001 *ApJ*, **561**, 106
NARLIKAR, J. V. & KEMBHAVI, A. K. 1980 *Fund. Cosmic Phys.*, **6**, 1

NARLIKAR, J. V. & PADMANABHAN, T. 2001 *ARA&A*, 39, 211
NARLIKAR, J. V., VISHWAKARMA, R. G. & BURBIDGE, G. 2002a *PASP*, 114, 1092
NARLIKAR, J. V., VISHWAKARMA, R. G., HAAJIAN, A., SOURADEEP, T., BURBIDGE, G. & HOYLE, F. 2002b *ApJ*, 585, 1
PENZIAS, A. A. & WILSON, R. W. 1965 *ApJ*, 142, 419
SHANE, C. D. & WIRTANEN, C. A. 1954 *AJ*, 59, 285
STEINHARDT, P. J. TUROK, N. 2002 *Science*, 296, 1436
DE VAUCOULEURS, G. 1961 *AJ*, 66, 629
WEINBERG, S. 1979 *Phys. Rev. Lett.*, 43, 1566

10

Red giants: then and now

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Fred Hoyle's work on the structure and evolution of red giants, particularly his pathbreaking contribution with Martin Schwarzschild (Hoyle and Schwarzschild 1955), is both lauded and critically assessed. In his later lectures and work with students in the early 1960s, Hoyle presented more physical ways of understanding some of the approximations used, and results obtained, in that seminal paper. Although later ideas by other investigators will be touched upon, Hoyle's viewpoint – that low-mass red giants are essentially white dwarfs with a serious mass-storage problem – is still extremely fruitful. Over the years, I have further developed his method of attack. Relatively recently, I have been able to deepen and broaden the approach, finally extending the theory to provide a unifying treatment of the structure of low-mass stars from the main sequence though both the red-giant and horizontal-branch phases of evolution. Many aspects of these stars that had remained puzzling, even mysterious, for decades have now fallen into place, and some questions have been answered that were not even posed before.

With low-mass red giants as the simplest example, this recent work emphasizes that stars, in general, may have at least *two* distinct but very important centres: (i) a *geometrical* centre, and (ii) a separate *nuclear* centre, residing in a shell outside a zero-luminosity dense core for example. This two-centre perspective leads to an explicit, analytical, asymptotic theory of low-mass red-giant structure. It enables one to appreciate that the problem of understanding why such stars become red giants is one of anticipating a remarkable yet natural structural bifurcation that occurs in them. This bifurcation occurs because of a combination of known and understandable

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