STANDARD COSMOLOGY AND ALTERNATIVES:
A Critical Appraisal

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■ **Abstract**   This review takes a critical look at the cosmological scenario at the turn of the century by examining the available cosmological models in the light of the present observational evidence. The center stage is held by the big bang models, which are collectively referred to here as standard cosmology (SC) and its extensions. SC itself is characterized by a seven parameter set of models based on Einstein's general theory of relativity. The seven parameters are H_0, Ω_B, Ω_{DM}, Ω_Λ, Ω_R (describing the background universe, and A, n (specifying the amplitude and power law index of initial fluctuation spectrum). The extended SC includes extrapolations of the SC to earlier epochs when the mean energies of the particles were greater than about 100 GeV. The strength of the SC is seen to lie in its successful prediction of the expansion of the universe, the abundance of light nuclei, and the spectrum and anisotropies of the cosmic microwave background (CMBR). The SC has led to a whole class of theories of structure formation, which are, in principle, testable observationally. The subject of twentieth century cosmology gained considerably from occasional ideas different from the SC; some of these are briefly outlined and placed in historical perspective. Currently there is only one alternative cosmology, the quasi steady state cosmology (QSSC), that has been developed to a stage where it can be compared with observations and also with the SC. Although the SC does appear quite successful, there are still many unresolved issues that keep the cosmological scene fairly open.

1. INTRODUCTION

The hallmark of a mature branch of science is that observations are ahead of theoretical framework but not significantly ahead. Judged by this criterion, cosmology became a mature scientific discipline in the past two decades—though several leading cosmologists of previous generations (who have contributed to this event) will disagree with such an appraisal. What everyone will agree with, however, is that the next two decades will certainly see a host of observational inputs and theoretical developments taking place in this area. These developments will sharpen (and could even rule out) currently favored theoretical models and

could also throw open fresher challenges for both observational and theoretical cosmology. The purpose of this review is to critically examine the current status of cosmology, especially with regard to crucial observational tests, and present an outlook for the future.

The review is organized as follows. The next section describes the framework of standard cosmology (SC) and sets up the notation for the review. Sections 3 and 4 cover the foundations, frontiers, and the successes of standard cosmology. A critical discussion of SC is taken up in Section 5 concentrating on the observations that either strongly constrain or marginally rule out the favorite models. The next two sections showcase the alternatives, concentrating on the quasi-steady state cosmology (QSSC) as a key prototype. Section 8 describes weaknesses of the QSSC, and the last two sections present the future outlook as envisaged by the authors.

2. FRAMEWORK OF STANDARD COSMOLOGY

All the well-developed models of SC start with two basic assumptions: (*a*) The large-scale structure of the universe is essentially determined by gravitational interactions and hence can be described by Einstein's theory of gravity. (*b*) The distribution of matter in the universe is homogeneous and isotropic at sufficiently large scales, and the necessary scale at which such a smoothness is observed can be self-consistently determined by the model. (There are a few theories that do not conform to these assumptions; we are not concerned with such models in this review.) We use notation commonly found in current literature in cosmology and in standard textbooks, e.g., Weinberg (1972), Narlikar (1993), Padmanabhan (1993), Coles & Lucchin (1995), and Peacock (1999).

These two assumptions turn out to be fairly powerful. The first assumption requires the geometry of the universe to be determined via Einstein's equations, with the stress tensor of matter $T_k^i(t, \mathbf{x})$ acting as the source. The second assumption shows that the large-scale geometry can be described by a metric of the form

$$ds^2 = dt^2 - S^2(t) \left[\frac{dr^2}{1 - kr^2} + r^2 (d\theta^2 + \sin^2 \theta \, d\phi^2) \right] \qquad (1)$$

in a suitable set of coordinates called comoving coordinates. (We use the units with $c = 1$ throughout the review.) If Einstein's equations have to be satisfied with such a metric, it is necessary that the stress tensor—when averaged over sufficiently large scales—has the form $T_k^i = \text{diag}[\rho(t), -P(t), -P(t), -P(t)]$, with the functions $\rho(t)$, $P(t)$, $S(t)$ satisfying the equations

$$\frac{\dot{S}^2 + k}{S^2} = \frac{8\pi G}{3} \rho; \quad \frac{d(\rho S^3)}{dt} = -P \frac{dS^3}{dt}. \qquad (2)$$

These are two equations connecting three unknown functions. The system is closed by providing information about the nature of the source in the form of an equation

of state connecting ρ and P. Given such a relation, the second equation in (2) can be integrated to provide ρ as a function of S, which in turn can be used in the first equation in (2) to determine S as a function of t.

It is important to stress that *absolutely no progress in cosmology can be made until a relationship between ρ and P is provided*. This fact, in turn, brings to focus two issues not often adequately emphasized.

1. If we assume that the source is made of normal laboratory matter, then the relationship between ρ and P depends on our knowledge of how the equation of state for matter behaves at different energy scales. This information needs to be provided by atomic physics, nuclear physics, and particle physics. Cosmological models can at best be only as accurate as the input physics about T_k^i is. Any definitive assertion about the state of the universe is misplaced if the knowledge about T_k^i, which it is based upon, is itself speculative or nonexistent at the relevant energy scales. At present we have laboratory results testing the behavior of matter up to about 100 GeV, and hence, if particle and nuclear physicists do their jobs properly, we can, in principle, determine the equation of state for matter up to 100 GeV. By and large, the equation of state for normal matter in this domain can be taken to be that of an ideal fluid, with ρ giving the energy density and P giving the pressure. The relation between the two is of the form $P = w\rho$, with $w = 0$ for nonrelativistic matter and $w = (1/3)$ for relativistic matter, and radiation.

2. The situation becomes more complicated when we realize that it is entirely possible for the large-scale universe to be dominated by matter whose presence is undetectable at laboratory scale. For example, large-scale scalar fields dominated either by kinetic energy or nearly constant potential energy could exist in the universe and will not be easily detectable by laboratory scale. Such systems will also have an equation of state in the form $P = w\rho$, with $w = 1$ (for kinetic energy dominated scalar field) or $w = -1$ (for potential energy dominated scalar field). While the conservative procedure for doing cosmology would be to use only known forms of T_k^i on the right hand side of Einstein's equations, this has the drawback of preventing progress in our understanding of nature, because cosmology could be the only testing ground for the existence of forms of T_k^i, which are difficult to detect by laboratory scales.

One of the key issues in modern cosmology has to do with the conflict in principle between the two issues listed above. Suppose a model based on conventional equations of state, adequately tested in the laboratory, fails to account for a cosmological observation. Should one treat this as a failure of the cosmological model or as a signal from nature for the existence of a source T_k^i not seen by laboratory scales? There is no easy answer to this question, and we focus on many facets of this issue in the coming sections.

If $P = w\rho$, it follows immediately from the Equation (2) (taking $k = 0$, for simplicity) that

$$\rho \propto S^{-3(1+w)}; \quad S \propto t^{2/[3(1+w)]}. \tag{3}$$

For example, $\rho \propto S^{-4}$, $S \propto t^{1/2}$ if the source is relativistic and $\rho \propto S^{-3}$, $S \propto t^{2/3}$ if the source is nonrelativistic. In the case of a radiation dominated universe, the time t and temperature T (expressed in energy units) are related by

$$\left(\frac{t}{1 \text{ sec}} \right) \cong g_R^{-1/2} \left(\frac{T}{1 \text{ MeV}} \right)^{-2}, \tag{4}$$

where g_R is the effective number of degrees of freedom of relativistic particles at this epoch (e.g., Padmanabhan, 1993:87)

In the case of a scalar field, $\rho \propto S^{-6}$, $S \propto t^{1/3}$ if the kinetic energy dominates and $\rho = $ constant, $S \propto \exp(Ht)$ if a constant potential energy term dominates. In the last case, the universe expands exponentially while all other cases lead to a power law expansion. In any realistic cosmological scenario one expects the equation of state for matter to vary gradually with energy, and thus we will expect different rates of expansion during different epochs in the evolution of the universe.

The equation of state $P = -\rho$ for a potential energy dominated scalar field is indistinguishable from a cosmological constant Λ in Einstein's equations. Hence we often refer to such a term as cosmological constant and denote its contributions to various physical quantities by a subscript Λ. Also note that a T_k^i of this form, arising from a scalar field, violates positive energy constraints.

We next turn to some mathematical features of the space/time geometry described above. For normal matter with $P > 0$, $\rho > 0$, Einstein's equations require S to vanish at some finite time in the past. This epoch of mathematical singularity has no physical relevance for two reasons. (*a*) It is trivial to remove this singularity by postulating a suitable form of equation of state for matter at high energies. Until the issue of equation of state for matter is settled by some other noncosmological procedure, such a possibility cannot be ruled out. (*b*) At sufficiently high energies classical gravity will cease to be valid, and the issue of singularity cannot even be addressed in the conventional framework of deterministic space/time geometry. We need to wait for a full theory of quantum gravity to tackle this question. It is, however, convenient to set the origin of time coordinates at this event of hypothetical, classical singularity for the purpose of reference.

Since Einstein's equations are second-order differential equations, a unique solution requires specification of S and $\dot{S}$ at some instant of time, which could be taken as the current epoch $t = t_0$ when the time coordinate is measured from the fiducial singularity. Instead of specifying S and $\dot{S}$, it is more convenient to provide the value of the Hubble constant $H_0 = (\dot{S}/S)$ and the matter density ρ_0 at the present epoch. The latter is measured in units of the critical density $\rho_c \equiv (3H_0^2/8\pi G)$ and is usually denoted by $\Omega_0 = (\rho_0/\rho_c)$. We also write $H_0 = 100h \text{ km s}^{-1}\text{Mpc}^{-1}$, where h is a dimensionless parameter currently believed to lie in the range $0.55 \lesssim h \lesssim 0.75$. The values of H_0, Ω_0 along with the equation of

state, completely determine the background cosmology. It is clear from Einstein's equations that Ω_0 is greater than, equal to, or less than one if $k = +1, 0, -1$, respectively; thus Ω_0 has a direct bearing on the spatial geometry of the universe.

It is therefore no surprise that two of the holy grails of observational cosmology are the parameters H_0 and Ω_0. Of these, H_0 is directly related to the rate of change of the scale factor of the universe. On the other hand, Ω_0 depends on the total amount of energy density in the universe that drives the expansion and could contain contributions from some esoteric form of matter not yet detected in the laboratory. Because of this, Ω_0 is often subclassified by type, according to whether it is contributed by baryons (Ω_B), dark matter (Ω_{DM}) radiation (Ω_R), cosmological constant (Ω_Λ), etc. Determination of the values of each of these parameters is also a task for the observational astronomer.

3. STANDARD COSMOLOGY: FOUNDATIONS AND FRONTIERS

Based on the mathematical framework outlined above, one can develop the formalism of standard cosmology (SC) that currently enjoys a fair amount of support among theoreticians and observers. Despite the adjective "standard," the actual details of what constitutes SC may differ from researcher to researcher, and so we begin by identifying the different ingredients of what we call SC in this review.

It is convenient to divide the discussion of SC into the description of the smooth background universe and the observed universe with structures existing at different scales. We begin with the smooth universe.

3.1. Description of the Smooth Universe in SC

It was pointed out in the last section that the geometry of the background universe is completely determined if (*a*) the equation of state at all energies is specified and (*b*) the present values of Ω_0 and H_0 are specified. The prescription of (*a*), in turn, requires specification of the Ω for each of the constituents of stress tensor, so that different equations of state may come into play at different epochs. It is incorrect to assume that the behavior of the matter sector can be "guessed" from the present knowledge of particle physics. Nor could one introduce principles such as Occam's razor in this context. The pragmatic approach to cosmology requires fitting a multiparameter model of background cosmology against a sufficiently accurate set of observations to determine all the free parameters.

Observations indicate that, in addition to H_0, four more free parameters are required to describe the background universe at energies below 50 GeV. (It is not possible to describe the universe at higher energies until high energy physics becomes as mature a branch of science as cosmology.) These are Ω_B, Ω_R, Ω_{DM}, and Ω_Λ describing the Ω contributed by baryonic matter, radiation, and dark matter including weakly interacting massive particles (e.g., massive neutrinos),

and cosmological constant, respectively. The first two certainly exist; the existence of last two is probably suggested by observations and is definitely not contradicted by any observations. Of these, only Ω_R is well constrained and other quantities are plagued by both standard and systematic errors in their measurements. The background universe in SC should be taken as a five-parameter model.

The evolution of a smooth universe in SC is characterized by two important epochs (e.g., see Narlikar 1993, Padmanabhan 1993): (*a*) The first is the radiation dominated epoch that occurs at redshifts greater than $z_{eq} \approx (\Omega_{DM}/\Omega_R) \approx 10^4$. For $z \gtrsim z_{eq}$, the energy density is dominated by hot relativistic matter, and the universe is very well approximated as a $k = 0$ model with $S(t) \propto t^{1/2}$. (*b*) The second phase occurs for $z \ll z_{eq}$, in which the universe is dominated by matter and—in some cases—the cosmological constant. The form of $S(t)$ in this phase depends on the relative values of Ω_{DM} and Ω_Λ. In the simplest case, with $\Omega_{DM} \approx 1, \Omega_\Lambda = 0, \Omega_B \ll \Omega_{DM}$, the expansion is a power law with $S(t) \propto t^{2/3}$. During both the epochs, the temperature of the radiation varies as $T \propto S^{-1}$. When the temperature falls below $T \approx 10^3$ K, neutral atomic systems form in the universe and photons decouple from matter. In this scenario, a relic background of such photons with Planckian spectrum at some nonzero temperature will exist in the present-day universe. The present theory is, however, unable to predict the value of T at $t = t_0$. It is therefore a free parameter in SC, and we use $\Omega_R \propto T_0^4$ instead of T_0 in this review.

The real universe, of course, has structures at smaller scales, which need to be understood within the cosmological frame work. We next specify the features of SC related to the formation of structures in the universe.

3.2. Structure Formation in SC

A strictly smooth universe will remain strictly smooth when evolved by Einstein's equations. In order to produce the inhomogeneities seen in the universe, it is necessary to assume in the SC that the universe contains small deviations from homogeneity in the energy density when $T \approx 50$ GeV. Out of the early work of Jeans (1902), Lifshitz (1946), Dicke & Peebles (1968), Zeldovich (1970), and others, there has emerged a well-defined and totally unambiguous procedure for evolving any initial inhomogeneity whatsoever, forward in time, as long as the perturbation is small (e.g., see Padmanabhan 1993) If the Fourier transform $\delta_{\mathbf{k}}(t)$ of the density contrast $\delta(t, \mathbf{x})$ is defined by

$$\delta(t, \mathbf{x}) \equiv \frac{\rho - \bar{\rho}}{\bar{\rho}}; \quad \delta_{\mathbf{k}}(t) = \int d^3\mathbf{x} \delta(t, \mathbf{x}) \exp i\mathbf{k}.\mathbf{x}, \qquad (5)$$

then the power spectrum of the perturbations is defined by the relation $P(k, t) = \langle |\delta_{\mathbf{k}}(t)|^2 \rangle$, where the averaging is either over a large volume or over several realizations. (The power spectrum depends only on the magnitude of the wave vector $\mathbf{k}$ because of the large-scale isotropy of the background universe.) When the perturbations are small, each mode evolves independently and the power spectra

at two different redshifts are related by

$$P(k, z_f) = Q(k, z_f, z_i, \text{bg})P(k, z_i), \qquad (6)$$

where Q (called transfer function) depends only on the five parameters of the background universe (denoted by "bg") and not on the initial power spectrum. Figure 1 shows the form of Q for a selected class of cosmologies. This arises as follows (for details, see Padmanabhan 1993):

The rate of growth of small perturbations is essentially decided by two factors: (*a*) the relative magnitudes of the proper wavelength of perturbation $\lambda_{\text{prop}}(t) \propto S(t)$ and the Hubble radius $d_H(t) \equiv (\dot{S}/S)^{-1}$, and (*b*) whether the universe is radiation dominated or matter dominated. At sufficiently early epochs, the universe will be radiation dominated and $d_{\text{H}}(t) \approx t$ will be smaller than the proper wavelength $\lambda_{\text{prop}}(t) \propto t^{1/2}$. The density contrast of such modes, which are bigger than the Hubble radius, will grow as S^2 until $\lambda_{\text{prop}} = d_H(t)$. (When this occurs, the perturbation at a given wavelength is said to enter the Hubble radius.) When $\lambda_{\text{prop}} < d_H$ and the universe is radiation dominated, the perturbation does not grow significantly and increases at best only logarithmically. Later on, when the universe becomes matter dominated for $t > t_{\text{eq}}$, the perturbations again begin to grow in
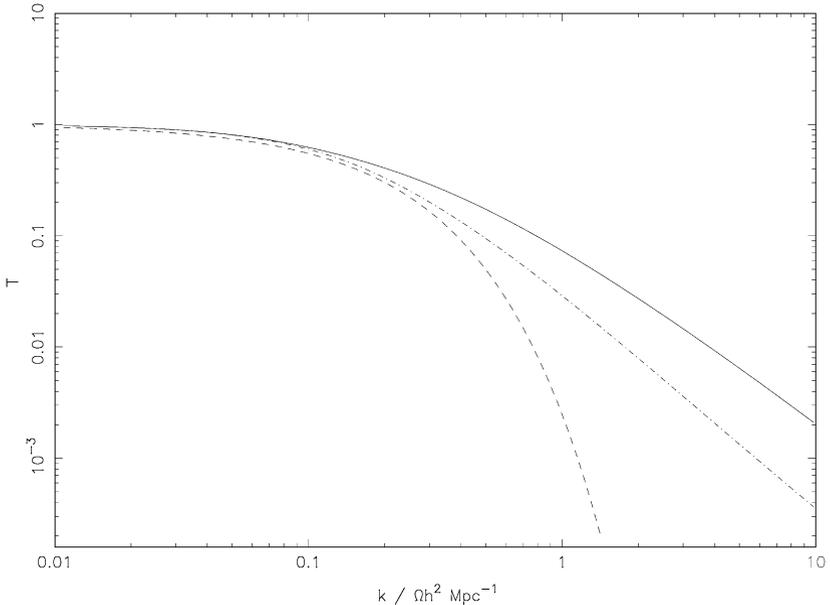

Figure 1   The transfer function for density fluctuations in different cosmologies. (*Top curve*) A standard cold dark model; (*middle curve*) a model with cold and hot dark matter in the proportion 30%–70%; (*bottom curve*) a purely hot dark matter model that is shown just for comparison, see Padmanabhan (1993).

proportion to $S(t)$. It follows from this result that modes with wavelengths greater than $d_{eq} \equiv d_H(t_{eq})$—which enter the Hubble radius only in the matter dominated epoch—continue to grow at all times, while modes with wavelengths smaller than d_{eq} suffer lack of growth in comparison with longer wavelength modes, during the period $t_{enter} < t < t_{eq}$ (Meszaros 1975). This fact leads to a distortion of the shape of the primordial spectrum by suppressing the growth of small wavelength modes in comparison with longer ones.

Because Q depends on k, the *shape* of the final spectrum changes during the evolution in a well-defined manner. Hence, the fluctuations in the universe at say $z_f \approx 10^3$ will be a direct product of the initial fluctuations and a transfer function with the latter depending only on the background cosmology. Very roughly, the shape of $Q(k)$ can be characterized by the behavior $Q(k) \propto k^{-4}$ for $k > k_{eq}$ and $Q \approx 1$ for $k < k_{eq}$. The wave number k_{eq} corresponds to the length scale

$$d_{eq} = d_H(z_{eq}) = (2\pi/k_{eq}) \approx 13(\Omega h^2)^{-1} \text{Mpc} \qquad (7)$$

(e.g., Padmanabhan, 1993:75). The spectrum at wavelengths $\lambda \gg d_{eq}$ is undistorted by the evolution since Q is essentially unity at these scales. Further evolution can eventually lead to nonlinear structures seen today in the universe.

It is now clear that the only new input that structure formation scenarios require is the specification of the initial perturbation at all relevant scales. This specification requires one arbitrary function of the wavenumber $k = 2\pi/\lambda$. The following points need to be emphasized regarding this initial fluctuation spectrum.

1. The actual amplitude of the fluctuations as well as the shape at $z = 10^3$ depends both on the initial fluctuation and the background cosmology. However, the fluctuations at largest scales have to be at least $\delta \simeq 10^{-5}$ at $z = 10^3$ if these have to evolve and form the observed nonlinear structures by $z = 0$.

2. It can be proved that known local physical phenomena that arise from laws tested in the lab, and acting at $T < 50$ GeV in a medium with $(P/\rho) > 0$, are incapable of producing the initial fluctuations of required magnitude and spectrum (e.g., Padmanabhan 1996, p. 458). The initial fluctuations in SC therefore must be treated as arising from physics untested at the moment.

3. Contrary to claims often made in the literature, inflationary models are not capable of uniquely predicting the initial fluctuations (Liddle & Lyth 2000). In other words, it is possible to come up with viable inflationary potentials that are capable of producing any reasonable initial fluctuation one wants. Hence, there is no predictive power in inflation. This is why we do not consider it as a part of SC in this review.

A prediction of the initial fluctuation spectrum was indeed made by two people who were years ahead of their times. Harrison (1970) and Zeldovich (1972) predicted, based on very general arguments of scale invariance, that the initial fluctuations must be Gaussian with a power spectrum $P = Ak^n$ with $n = 1$.

Considering the simplicity and importance of this result, we briefly review the arguments leading to the choice of $n = 1$.

If the power spectrum is $P \propto k^n$ at some early epoch, then the power per logarithmic band of wave numbers is $\Delta^2 \propto k^3 P(k) \propto k^{(n+3)}$. Further, when the wavelength of the mode is larger than the Hubble radius, $d_H(t) = (\dot{S}/S)^{-1}$ during the radiation dominated phase, the perturbation grows as S^2, making $\Delta^2 \propto S^4 k^{(n+3)}$. We need to determine how Δ scales with k when the mode enters the Hubble radius $d_H(t)$. The epoch S_{enter} at which this occurs is determined by the relation $2\pi S_{enter}/k = d_H$. Using $d_H \propto t \propto S^2$ in the radiation dominated phase, we get $S_{enter} \propto k^{-1}$, so that

$$\Delta^2(k, S_{enter}) \propto S_{enter}^4 k^{(n+3)} \propto k^{(n-1)}. \tag{8}$$

It follows that the amplitude of fluctuations is independent of scale k at the time of entering the Hubble radius, only if $n = 1$, which was the essence of the Harrison-Zeldovich argument. We also note that the power spectrum of gravitational potential P_ϕ scales as $P_\phi \propto P/k^4 \propto k^{(n-4)}$. Hence the fluctuation in the gravitational potential (per decade in k) $\Delta_\phi^2 \propto k^3 P_\phi$ is proportional to $\Delta_\phi^2 \propto k^{(n-1)}$. This fluctuation in the gravitational potential is also independent of k for $n = 1$, clearly showing the special nature of this choice.

Since (*a*) this was a genuine prediction and since (*b*) scale invariance is likely to outlive inflationary models, we consider this to be a part of SC. In other words we take the initial fluctuation spectrum at $T = 50$ GeV to be of the form $P = Ak^n$, with A arbitrary and n being close to unity. (It is not possible to take n strictly equal to unity without specifying a detailed model. The reason has to do with the fact that scale invariance is always broken at some level and this will lead to a small difference between n and unity).

As an aside, we stress that, because of point 3 and because of comments in the above paragraph, verification of $n = 1$ by any observation is not a verification of inflation. At best it verifies the far deeper principle of scale invariance. At present, there exists no direct observational support for inflation. Nor does there exist any unique, falsifiable prediction from inflation.

Given the above description, the full model of SC is based on seven parameters. Of these, five parameters ($H_0, \Omega_B, \Omega_{DM}, \Omega_\Lambda, \Omega_R$) determine the background universe and the two parameters A, n, specify the initial fluctuation spectrum.

3.3. Extensions of SC

We have defined the SC as a seven-parameter theory with the values of parameters to be determined by comparison with observations. If one is willing to speculate regarding the behavior of the universe at energies higher than those tested in the laboratory, one can extend the domain of SC to earlier epochs. All of these models (one example being the inflationary universe) add a new set of free parameters to the theory, using some of the above seven parameters that are sought to be "explained." This approach is of tremendous theoretical significance (and must be

pursued) with the caveat that the number of new parameters introduced into the theory should be less than the number of observations such a theory "explains." At present no such model with compelling structural beauty is available. It is, therefore, necessary to stick to the definition of SC given above if one wants to do cosmology as a branch of science.

Since the seven parameters are treated as inputs in the version of SC outlined here, we cannot even address the question of their relative or absolute values. For example, if the observations suggest that (e.g., see Bagla et al. 1996) the present-day universe has $\Omega_{DM} \approx 0.35$ and $\Omega_\Lambda \approx 0.60$, then one would be very curious to know why they are so close to each other at the current epoch. (Note that these two parameters will vary with epoch at different rates with time, and hence, their being different from each other by only a factor of two today is a striking coincidence.) In such a universe, one would also like to know why $\Omega_{DM} + \Omega_\Lambda = 0.95$, which is a value very close to $\Omega = 1$. Such questions are fascinating and should definitely be addressed at some future date. It is, however, likely that the answers to such questions lie in the physics of energies greater than 50 GeV and hence cannot be settled uniquely by cosmological considerations alone.

The important point to remember is that the SC—even with seven free parameters—is a predictive and falsifiable theory; hence quite a bit of interesting cosmology can be done without speculating about the relative values or origins of these parameters. These parameters can be thought of as analogues of coupling constants and mass ratios in the standard model of electroweak interactions in particle physics. The electroweak theory has far more (27) free parameters than does standard cosmology (Kaul 1983), a fact reflected in the unexplained values for the ratios of these parameters–like the masses of the muon and the electron. Nevertheless, the electroweak model (just like the SC) is a successful, predictive, falsifiable theory. This is the spirit in which the SC is defined and handled in this review.

4. SUCCESSES OF THE STANDARD MODEL

Given this set of seven parameters, it is interesting to ask what predictions SC makes. To discuss this systematically, consider the key features of a low-energy universe determined by the seven parameters.

4.1. Successes of the Background Model

Given the initial particle densities around 50 GeV and the known interactions, one can evolve the universe forward in time. Because low-energy interactions conserve baryon numbers, the photon-to-baryon ratio in such a universe does not change significantly. It is fixed by the initial conditions. The smooth universe has, by definition, the same temperature at all points and its evolution is homogeneous. We now briefly summarize the key events in the evolution of such a universe.

1. As the universe expands and cools, different physical interactions freeze out at different epochs. When $T \approx$ (few) MeV, the neutrinos decouple from the rest of the matter and form a noninteracting background with a specific spectrum. At the time of decoupling, the temperature T_ν characterizing the Fermi-Dirac distribution is the same as the photon temperature. At a later stage, electrons and positrons annihilate and dump the energy on radiation, thereby increasing photon temperature. The neutrinos do not share this energy because they have already decoupled. These facts allow the unambiguous prediction of the existence of a neutrino background today, with a definite form for the spectrum and a definite ratio for $(T_\nu/T_\gamma) = (4/11)^{1/3} \cong 0.71$ (Alpher et al. 1953; for a textbook discussion, see e.g., Padmanabhan 1993, p. 94). Though current technology is incapable of testing this prediction, it will certainly be tested sometime in the future.

2. Around $T \approx$ (few) MeV, nucleosynthesis takes place in the SC, leading to the production of light elements. The abundances, which can be calculated from known laws, depend crucially on Ω_B and the number of species of neutrinos. What is more, the helium, deuterium, and lithium abundances depend on these parameters in a different fashion. It turns out that (*a*) the helium abundance constrains the number of neutrino species to three; a result predicted by cosmology before being verified in the lab from the decay of Z^0. It should be stressed that SC was in no way "designed" to give three species of neutrinos; the consistency of this prediction (which arises without any fine-tuning in the SC) with the findings of particle physics is noteworthy. (*b*) It is possible to choose a range of values for Ω_B such that the observed values of helium, deuterium, and lithium abundances can be explained. One essentially requires $0.01 \lesssim \Omega_B h^2 \lesssim 0.04$. The existence of such a region of concordance is also a nontrivial feature of the SC. If the synthesis of light elements did not take place along the lines envisaged in SC, it is not easy to explain why such a region of concordance should exist. For example, the nucleosynthesis in stellar burning and in supernova leads to a very different dependence of the abundances on the photon-to-baryon ratio.

3. The SC inevitably introduces a hot, radiation dominated phase in the early universe with a high photon-to-baryon ratio. Because these photons will decouple from matter when $T \approx 10^3$K, there will exist a cosmic background of radiation (CMBR) with a Planck spectrum in the present-day universe. The following point needs to be stressed: While the SC cannot provide the value of the current CMBR temperature (being related to Ω_R, which is an input parameter), it does make a definitive prediction of the existence of a cosmic radiation background with a Planckian spectrum at some $T \neq 0$. No other model makes such a prediction in a natural fashion; alternate models need to produce the thermal radiation from a nonthermal one by some physical process, as an afterthought. What is more, no other model predicted the

existence of such a thermalized spectrum before it was discovered. The existence of CMBR is therefore a definite plus for SC.

4. In the SC, the universe is dominated by Ω_B, Ω_{DM} and Ω_Λ during $z \ll 10^3$ and as such a host of indirect cosmological measurements constrain these three parameters. For example, (*a*) the number counts of galaxies (for a review, see Fergusson et al. 2000), (*b*) the age of the universe (for a review, see Lineweaver 1999), and the (*c*) statistical distribution of gravitationally lensed quasars (Falco et al. 1998) all depend on these four cosmological parameters in a different manner. There is no a priori reason for any range of values for these parameters to be consistent with these observations. However, that is indeed the case.

5. There are two predictions from SC that are, in principle, falsifiable sometime in the future: The first is the existence of a neutrino background with a temperature of $T_\nu = 1.9$ K, which, as we mentioned earlier, should be detectable in the future. The second one is the fact that SC predicts the universe to be expanding during the entire redshift range of $0 < z \lesssim 10^3$ so as to cool the CMBR. If a systematic population of distant objects is found with blueshifted spectra, it signals a contracting phase for the universe and rules out the SC.

4.2. Successes of the Paradigm for Structure Formation in SC

Structure formation in SC proceeds through the evolution of initial inhomogeneities (described by two parameters A, n) via gravitational clustering. This leads to several additional consequences.

First, the SC makes an unequivocal prediction that, because of small fluctuations in the matter distribution, small fluctuations will exist in the CMBR. This paradigm predicts that temperature anisotropies in the CMBR will be at least of fractional order 10^{-6} if the structures were to become nonlinear by $z = 0$. This is a definite prediction of SC. The COBE satellite mission, launched specifically to test this prediction, did in fact find anisotropies in the CMBR (Smoot et al. 1992). It must be stressed that proponents of alternative models had claimed before 1992 the smoothness of CMBR as a major weakness of the SC and had, therefore, argued against the structure formation paradigm of SC. The COBE results can therefore be seen as a feather in the cap for SC, because the SC predicted it.

Having said that, one must be careful not to overstate the claim, as some proponents of the SC have done. The COBE detection does not verify inflation; nor is it capable of determining cosmological parameters in a unique manner, for reasons described in the previous section. It only verifies the paradigm for structure formation and provides values for A and n with reasonable accuracy.

Where SC really scores is in the fact that it can do far better regarding temperature anisotropies. It predicts a generic shape for the spectrum of temperature anisotropies, shown schematically in Figure 2*a*. The plot gives temperature anisotropies in a suitably normalized unit as a function of the angular quantum
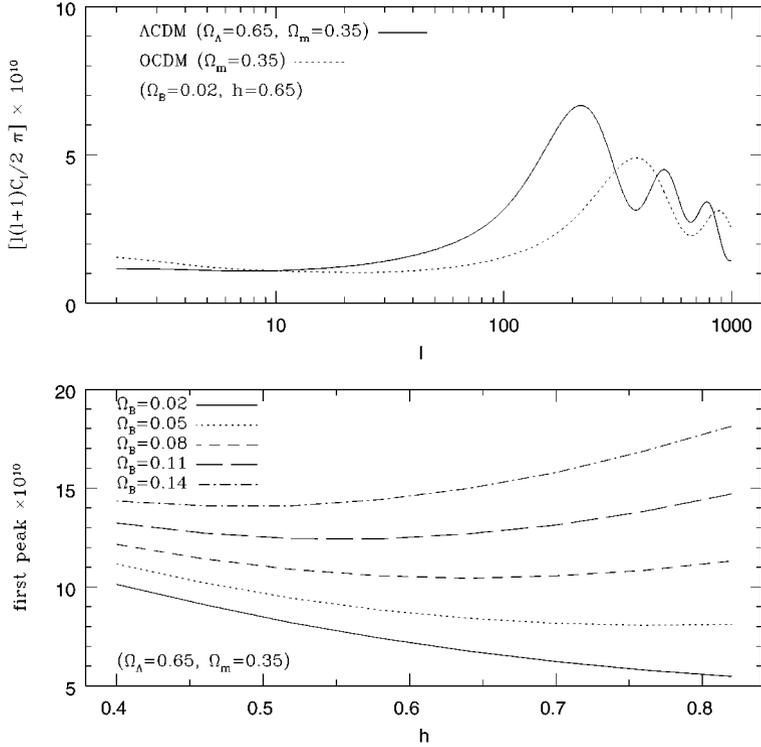
Figure 2 (*a*) The temperature anisotropies in two cosmological models. The *x*-axis is labeled in terms of the angular quantum number *l*, which is inversely proportional to the angular scale on the sky. The *y*-axis gives $\Delta T/T^2$ in suitably normalized units. The two models have the same amount of matter energy density, but one of the models has cosmological constant. Λ *CDM*, model with cosmological constant and cold dark matter, with $\Omega_{\text{total}} = 1$; OCDM, open model with cold dark matter in which $\Omega_{\text{total}} \approx \Omega_{\text{DM}} < 1$. It is clear that the pattern of anisotropies depends crucially on the cosmological model. Figure 2(*b*) The height of the first acoustic peak in the same normalized units used in Figure 2(*a*). The cosmological model has $\Omega_{\text{total}} = 1$, with $\Omega_{\Lambda} = 0.65$. Models with different baryonic content are illustrated. The Hubble constant in units of $H_0 = 100$ is along the abscisa.

number *l*, which is inversely related to the angular scale in the sky. We now briefly describe how this comes about.

In the simplest scenario, the primary anisotropies of the CMBR arise from three different sources. (*a*) The first is the gravitational potential fluctuations at the last scattering surface (LSS), which will contribute an anisotropy $(\Delta T/T)^2_\phi \propto k^3 P_\phi(k)$, where $P_\phi(k) \propto P(k)/k^4$ is the power spectrum of gravitational potential ϕ. This anisotropy arises because photons climbing out of deeper gravitational wells lose

more energy on the average. (*b*) The second source is the Doppler shift of the frequency of the photons when they are last scattered by moving electrons on the LSS. This is proportional to $(\Delta T/T)^2_D \propto k^3 P_v U$, where $P_v(k) \propto P/k^2$ is the power spectrum of the velocity field. (*c*) Finally, we also need to take into account the intrinsic fluctuations of the radiation field on the LSS. In the case of adiabatic fluctuations, these will be proportional to the density fluctuations of matter on the LSS and hence will vary as $(\Delta T/T)^2_{\text{int}} \propto k^3 P(k)$. Of these, the velocity field and the density field (leading to the Doppler anisotropy and intrinsic anisotropy (described in second and third sources above) will oscillate at scales smaller than the Hubble radius at the time of decoupling since pressure support will be effective at these scales. At large scales, if $P(k) \propto k$, then

$$\left(\frac{\Delta T}{T}\right)^2_\phi \propto \text{constant}; \quad \left(\frac{\Delta T}{T}\right)^2_D \propto k^2 \propto \theta^{-2}; \quad \left(\frac{\Delta T}{T}\right)^2_{\text{int}} \propto k^4 \propto \theta^{-4}, \quad (9)$$

where $\theta \propto \lambda \propto k^{-1}$ is the angular scale over which the anisotropy is measured. Obviously, the fluctuations due to gravitational potential dominate at large scales whereas the sum of intrinsic and Doppler anisotropies will dominate at small scales. Since the latter two are oscillatory, we will expect an oscillatory behavior in the temperature anisotropies at small angular scales.

There is, however, one more feature we need to take into account. The above analysis is valid if recombination was instantaneous; but in reality the thickness of the recombination epoch is about $\Delta z \simeq 80$ (Jones & Wyse 1985, Padmanabhan 1993, chapter 3). This implies that the anisotropies will be exponentially damped at scales smaller than the length scale corresponding to a redshift interval of $\Delta z = 80$. The typical value for the peaks of the oscillation are at about 0.3–0.5 degrees depending on the details of the model. At angular scales smaller than about 0.1 degree, the anisotropies are heavily damped by the thickness of the LSS.

Because the final shape is a convolution of four distinct effects (three sources of anisotropy and the effect of finite thickness of the last scattering surface), the shape depends nontrivially on the seven parameters of SC, especially on the five parameters of the background cosmology. Of particular importance is the relative height of the first peak. This depends on the baryonic density and can be a sensitive probe of Ω_B. In addition, the location of the first peak in angular scale is a probe of the geometry of the universe and thus depends on the Ω_Λ and Ω_{DM}. These are illustrated in Figures 2*a* and *b*; Figure 2*a* compares the pattern of anisotropies for two different cosmological models. (The curves were generated using CMB-FAST) (see Seljak & Zaldarriaga 1996). Figure 2*b* illustrates the dependence of the height of the first peak on Ω_B and *h* in a model with $\Omega_\Lambda = 0.65$, $\Omega_m = 0.35$.

Given the density of information contained in the anisotropies, it is no surprise that a host of observations are in progress to determine this pattern. As a concrete example, it may be noted that the recent observations of the Boomerang and Maxima projects (de Bernardis et al. 2000, Hanany et al. 2000) have claimed the detection of the first acoustic peak. When these results are combined with previous
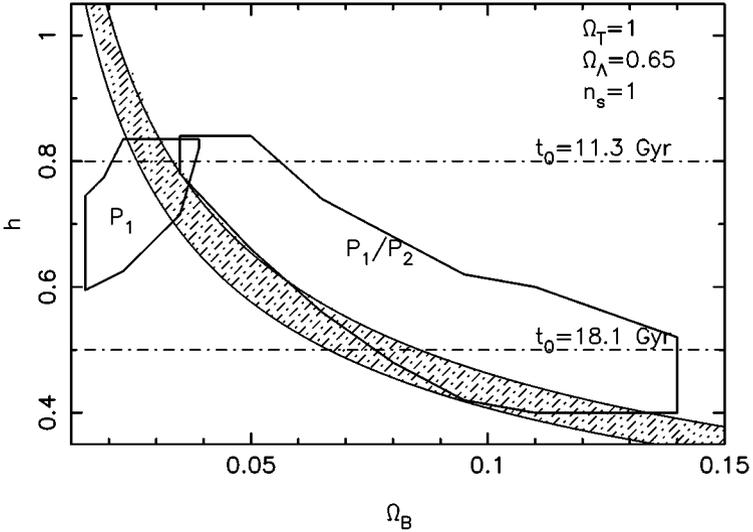
Figure 3 The range allowed by several observations in the $\Omega_B - h$ plane. The cosmological model is $\Omega_{total} = 1$, with $\Omega_\Lambda = 0.65$. The enclosed region in the left-hand corner (marked P_1) is obtained by requiring the height of the first Doppler peak to be consistent with Boomerang observations. The larger enclosed region (marked P_1/P_2) arises from the demand for consistency of the ratio of the heights of the first two Doppler peaks with the Boomerang observations. (*Shaded region*) The area allowed by primordial nucleosynthesis; (*dot-dashed lines*) the constant age of the universe. The age corresponding to a given curve is indicated. (Padmanabhan & Sethi 2000)

CMBR observations and galaxy survey results, it is possible to put bounds on several cosmological parameters. One of the many such analyses (Tegmark et al. 2000) claims that at a 95% confidence level the bounds (*a*) $0.02 < \Omega_B h^2 < 0.037$, (*b*) $0.1 < \Omega_{DM} h^2 < 0.32$, and (*c*) $\Omega_\Lambda < 0.76$. Figure 3 shows the constraints on Ω_B and h arising from Boomerang observations as well as other constraints (Padmanabhan & Sethi, 2000).

As we proceed to smaller length scales, the effects of nonlinear evolution of the density perturbation and the effects of gas dynamics make the results more difficult to interpret conclusively and uniquely. There are, however, some results that turn out to be more robust than others. The first is related to the root mean square fluctuation in the peculiar velocity field of matter at large scales (e.g., Bertschinger et al. 1990). This result can be used to determine the amplitude of the power spectrum around $R \approx 50h^{-1}$ Mpc, and one gets $\Delta (R = 50h^{-1}$ Mpc$) \approx 0.02$. This is consistent with reasonable range of parameters in SC. The second result is connected with an abundance of large clusters that could be used to determine the amplitude of the power spectrum at $R \approx 8h^{-1}$ Mpc, which put stronger constraints on the models. For example the parameter values

$h = 0.5$, $\Omega_0 \approx \Omega_{DM} = 1$, $\Omega_\Lambda = 0$ are ruled out by this observation when combined with COBE observations (Padmanabhan & Narasimha 1992, Efstathiou et al. 1992).

Another result is the measurement of cosmological parameters using supernova Ia as standard candle in the two HST Key Projects and the Supernova Cosmology Project (Perlmutter et al. 1999). The best fit to the data gives the line $0.8\Omega_{DM} - 0.6\Omega_\Lambda = -0.2 \pm 0.1$. This is consistent with an $\Omega_{DM} + \Omega_\Lambda = 1$ model if we take $\Omega_{DM} \simeq 0.3$, $\Omega_\Lambda \simeq 0.7$, although these parameters do not give the best fit statistically. (As Ω_B is very small compared with Ω_{DM}, we have used in these fits Ω_{DM} instead of $\Omega_M = \Omega_B + \Omega_{DM}$ referred to by the above authors.)

At small scales, the SC provides a sufficient amount of power for the formation of galaxy-like structures. In comparing the results of SC with observations at these scales, the following feature must be kept in mind. The theory only determines the root mean square fluctuations in the density field at any given scale. In the observed universe, it is certainly possible for 2σ and 3σ fluctuations of the density field to exist with a lower probability of $\exp(-n^2/2)$ for an $n\sigma$ deviation. If the typical 1σ fluctuation goes nonlinear at a redshift z_1, then the $n\sigma$ fluctuation at the same scale will go nonlinear at a higher redshift of

$$z_n = n(1 + z_1) - 1. \tag{10}$$

To see what this means, consider a typical 1σ galaxy-scale fluctuation that goes nonlinear at $z_1 = 2$. The above formula shows that a galaxy will form due to a 2σ fluctuation [with a relative probability of $\exp(-2) \approx 0.1$] at $z_2 = 5$; galaxies will form due to 3σ fluctuation [with a relative probability of $\exp(-4.5) \approx 0.01$] even at $z_3 = 8$. This simple calculation shows that the SC predicts structure formation to be a fairly extended process with one percent of all galaxies forming at redshift 8 and ten percent at redshift 5. As the technology improves and more and more of the high redshift universe becomes observationally accessible, one would expect to see an extended phase of structure formation and isolated incidences of such evolved structures as quasars, galaxies etc., at high redshifts. These can be interpreted as low-probability events originating from rare, high-σ peaks of the random field, and their occurrence is consistent with the SC.

5. WEAKNESSES OF THE STANDARD MODEL

In the previous section we reproduced arguments usually advanced by the typical believer in the SC. Notice that the majority of checks relate to the early universe and high redshift epochs. The emphasis of tests of the SC has shifted from studies that dominated the period from the 1950s to the 1970s of populations of low redshift ($z \lesssim 1$) objects to the predictions of relics of the early universe. We now take up the role of a critic of the SC. The bottom line of our argument is that while the SC

can claim successes on several fronts, it also has serious shortcomings which one should be aware of.

In the past few sections, we carefully defined SC as a family of theories bounded by a set of seven parameters, and we called attempts to extend the model to earlier epochs as "extended SC." In discussing the weaknesses of the standard approach, it is important to distinguish between the weaknesses of SC versus the weaknesses of extended SC, which tries to model the very early universe. We begin with weaknesses of the former.

5.1. Weaknesses of SC

Although defining SC as a parametrized cosmology allows certain precision and clarity to the model, it is not intellectually satisfying. While it has fewer free parameters than the well-accepted standard electroweak theory, cosmology is thought to be the place "where the buck stops." Ideally such a theory should have no free parameters! What is more, the theory requires three density parameters for baryons, nonbaryonic dark matter, and cosmological constant that are all of comparable value at the current epoch. This requires extreme fine-tuning of parameters, for which, until today, we have had no good reason.

The parameters are also severely constrained by the observations. Bagla et al. (1996) had carried out the exercise illustrated in Figure 4. There we plot the limits on the SC parameters h and Ω_0 from several observational constraints, including (*a*) the ages of globular clusters, (*b*) measurements of H_0, (*c*) abundance of rich clusters, and (*d*) abundance of high redshift objects. It is clear that the allowed range of parameters is narrow and some critics might even say nonexistent. The supporters of SC, while admitting the constraining nature of the data, have consistently argued that some of the constraints may become insignificant as data accumulate, whereas for others, a suitable way out may eventually be found. The critics of SC have argued that with so many constraints it is not wise to put all our cosmological eggs in one SC basket. We now highlight the constraints on Ω_Λ, Ω_B, and Ω_R.

1. The constraints are particularly severe on the cosmological constant. The history of twentieth century cosmology can identify epochs when invoking Λ was hailed as a major finding because observations happened to force the theory into a tight corner from where a suitable window of values of this parameter could rescue it (for example, see Gunn & Tinsley 1975). On other occasions it was discarded as an unnecessary encumbrance (see, for example, the proceedings of the IAU Symposium 124 held in Beijing in 1986, where there is no discussion of this parameter at all, except a brief reference to it in Malcolm Longair's (1986) summing up where he puts $\Lambda = 0$). Currently it is enjoying popularity. Models in which $\Omega_0 + \Omega_\Lambda = 1$, with the cosmological constant originating as a vacuum phase transition effect in the early universe, require extreme fine-tuning: The value of Λ today has to be around 10^{-108} times that prevailing during a grand unified theories
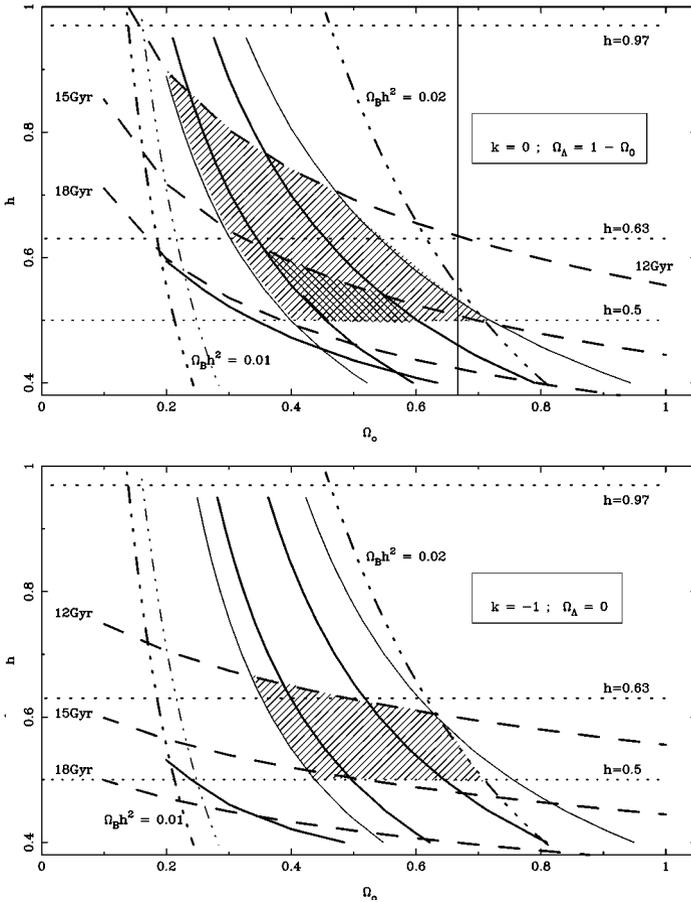
Figure 4   Summary of all the constraints on Ω_{DM} and h from different observations. (*Top*) $\Omega_\Lambda + \Omega_0 = 1$; (*bottom*) $\Omega_\Lambda = 0$, $\Omega_0 < 1$, with $\Omega_0 = \Omega_B + \Omega_{DM}$. (*Thick, broken lines*) Models of constant age, with $t_0 = $ (12 Gyr, 18 Gyr); (*thick, unbroken lines*) the region allowed by cluster abundance; (*thin lines*) the extent to which this region can be enlarged due to the uncertainty in COBE measurements of the temperature anisotropy. (*Thick dash-triple dot lines*) The constraints from primordial deuterium abundance (for $\Omega_B h^2 = 0.02$ and 0.01); (*thin line*) from deuterium abundance at high redshift; (*thick, unbroken line*) from the abundance of high redshift objects, obtained by requiring that a mass scale $10^{11} M_\odot$ should go nonlinear at $z \geq 2$. (*Cross-hatched area*) The region allowed without taking uncertainty in COBE normalization into account. If the uncertainties in the observations are pushed to the extreme limits, then the allowed parameter space corresponds to the *shaded region*. A somewhat less conservative interpretation of observations will lead to a much smaller allowed region (*cross-hatched area*). Here we have not used the bounds arising from values of the deceleration parameter and observation of deuterium abundance at high redshift. (For details, see Bagla et al. 1996.)

(GUT) phase transition or $\sim 10^{-120}$ of its value at the Planck epoch. A difference of even half an order of magnitude in this relic value would take its present value beyond the observationally permitted window (Weinberg 1988).

2. The SC claim of explaining light nuclear abundances should be seen against the backdrop of explaining abundances of all (more than 320) isotopes in the periodic table. With the exception of D, He, Li, Be, and B, other isotopes can be explained as made in stars. Indeed one could turn the argument around and argue that these handful of elements represent the measure of success of Gamow's original expectations of producing all elements in the hot big bang. Even to get these right, one has to fine-tune the baryon density-temperature relationship to $\rho_B \simeq 10^{-5} T_9^3$. Inserting the present value of $T_9 = 2.73 \times 10^{-9}$, gives the present value of $\rho_B \simeq 2 \times 10^{-31}$ g cm^{-3}. A rise of baryon density above this value would drastically reduce the predicted deuterium abundance. The constraint forces the SC to require a major proportion of dark matter found in the universe to be of nonbaryonic origin. If indeed it turns out to be the case, then it will be a major feather in the cap of SC. On the other hand, as Burbidge & Hoyle (1998) have argued, a case can now be made for making all the light nuclei also in stars, thus depriving the SC of one of its credible successes.

3. The strongest evidence in favor of the SC is the prediction of the cosmic microwave background. As we remarked in the last section, the primordial interpretation does not provide the present temperature of the relic radiation and T_0 is taken to be a free parameter determined by Ω_R. As pointed out by Assis & Neves (1995), apart from an early "guesstimate" of ~ 5K by Alpher & Herman (1948), Gamow himself on different occasions variously estimated the present temperature at values ranging from 7 K to 50 K. When one recalls that for a blackbody radiation the energy density goes as the fourth power of temperature, the above span of temperatures covers an energy uncertainty of four orders of magnitude. Although T_0 is probably the best-determined cosmological parameter today, an interpretation relating the present background temperature to other physical processes in the universe, when available, would clearly mark an improvement over the standard interpretation.

In summary, all objections to the SC, as defined before, are related to the fact that their numerical values are not determined by a more fundamental principle and need to be fine-tuned in an ad hoc manner. It is true that the standard electro-weak model does not explain the numerical values of the parameters (e.g., the mass ratio of muon and electron is not fixed by theory); but since cosmologists should strive to do better than particle physicists, this cannot be accepted as an excuse. Most attempts in literature to address these questions take one into extensions of SC, and we now discuss the difficulties faced by these attempts.

5.2. Weaknesses of the Extended SC

It has been argued (Narlikar 1999) that the very theoretical formulation of the SC has internal inconsistency. It is derived from Einstein's field equations, which predict the big bang singularity for reasonable equations of state. The action principle, as well as the local conservation laws, which are definable in a spacetime continuum with regular geometrical properties, break down at the singularity. In any other branch of physics an inconsistency of this kind would be looked on as a sign of imperfection of the theoretical framework and attempts would be made to look for a singularity-free theory. In the SC not only is the big bang often identified with the (mythical) "creation event." It is hardly treated as a negative feature.

It is usually argued that the singularity will eventually be removed by a more perfect model of quantum gravity. Indeed this could be a defense, provided one also admits that any physics done close to the singular epoch has to be treated with extreme caution, including any initial conditions assumed at the so-called quantum gravity epoch. Yet most of the work on structure formation and astroparticle physics that rests on developing primordial initial conditions, is presented with a definitiveness that belies the above caution. Some researchers have argued with equal definiteness in the past about models that are mutually exclusive! A survey of proceedings of Vatican Conferences of different decades will prove the point (O'Connell 1970, Bruck et al. 1982).

Consider, for example, the epoch of operation of GUT and inflation. The GUTs have not been experimentally tested at their characteristic energy of $\sim 10^{16}$ GeV; indeed the interest of particle physicists in the SC has been motivated by the availability of a scenario where their GUTs can be tested. However, the cosmological scenario of that epoch is not directly observable by any of the techniques currently available. Since all species except gravitons would have been in thermal equilibrium in such an epoch, the only direct signature of such an epoch will be the gravitational wave background. There is no model-independent prediction for this background; nor can we expect to put meaningful constraints on it from the planned gravity wave detectors. Thus a critic will ask whether applying a speculative theory to a speculative epoch constitutes "physics." It still could, provided one treated it as an exercise in consistency, rather than a definitive picture of the very early universe.

We have stressed in earlier sections that it is the job of particle physicists to predict the physics of the right-hand side of Einstein's equations at all energy scales, which could then be used by cosmologists to evolve the model. Attempts in the reverse direction have generally failed to produce meaningful results.

A comparison with stellar evolution is instructive. Many of the nuclear fusion reactions in stars have not been tested in the laboratory. However, there is enough repetitive evidence on stars to test the applications of these reactions and the HR diagram stands testimony for this fact. Thus the physics criterion of repeatability of an experiment is satisfied here. By contrast, the very early universe provides a nonrepetitive sequence of events to test these fundamental ideas, ideas that

extrapolate across huge untested domains spanning 12 powers of 10 in energy, 17 in temperature and over 50 in density.

Given these caveats, one could argue that there is still scope for understanding the universe in some framework other than that of SC, described in earlier sections. Against this background, we now briefly review the alternatives offered.

6. ALTERNATIVE COSMOLOGIES: A GENERAL SURVEY

From time to time since its development in the 1930s, alternatives to the SC have popped up, but none has shown as much tenacity for survival as SC. There are several reasons for this, including (*a*) the fact that the motivating reasons for the alternative models became less and less persuasive, (*b*) the human power and efforts needed to push an alternative theory further, as the observations advanced, could not be mobilized , and (*c*) the observational tests ruled out (or appeared to rule out) the alternative. The snowball effect arising from the social dynamics of research funding drove more researchers into the SC fold and contributed to the drying out of alternative ideas. Nevertheless in order to present a historical perspective of the motivations that prompted people to look for alternatives, we briefly mention a few (for a review, see Narlikar & Kembhavi 1980 and references therein). Since the review by Narlikar & Kembhavi, the only significant new alternative to have emerged is "quasi-steady state cosmology" (QSSC), which may be considered as possibly the best contender today among the alternatives. We discuss the QSSC in greater detail in the following section.

6.1. Universes with Rotation and Shear

In the volume devoted to Einstein's seventieth birthday, Kurt Gödel (1949) proposed the idea of a spinning universe, within the framework of GR, largely to demonstrate the "antiMachian" result (see Section 6.3), that in such a universe the distant parts (made of stars, galaxies, etc.) rotate with respect to the local inertial frame. In the mid-1950s, Heckmann & Schücking (1955) looked for spinning models in general with the hope that some might turn out to be nonsingular, i.e., without the big-bang type singularity. In this they were guided by the equation obtained by Raychaudhuri (1955),

$$\dot{\theta} + \frac{1}{3}\theta^2 - u_{;k}^k + 2(\sigma^2 - \omega^2) + \frac{1}{2}(\epsilon + 3p) - \lambda = 0. \tag{11}$$

Here σ and ω are, respectively, the shear and spin of the universe, θ the rate of change of its volume, ϵ its energy density, and p the pressure of the cosmic fluid. The velocity vector of the fluid is u^k. It is clear that the spin term goes against the collapse and the singularity while the shear term tends to help them. However, this equation turns out to not be enough to determine whether the singularity is avoidable; and it was finally established by the singularity theorems in the 1960s that the space/time singularity is an inevitable feature of relativistic

cosmology, unless one relaxes the so-called energy conditions (see Hawking & Ellis 1973).

The interest in anisotropic models, however, continued for a while in the expectation that some large-scale observation of the universe would turn up evidence for spin or shear. Observations of distant sources such as galaxies and radio sources show that they are nonrotating with respect to the local inertial frame to within 2.5×10^{-4} arcsec per year (Barbour & Pfister 1995, p. 364). Likewise, mappings of the microwave background have put stringent bounds on such anisotropies. Work on Bianchi models has also shown how initial anisotropies are quickly dissipated in an expanding universe. Hence anisotropic models are not currently popular.

6.2. Large Numbers Hypothesis

Dirac (1937) had drawn attention to the existence of large numbers relating constants/parameters of microphysics and cosmology. In particular, the large dimensionless ratios like that of the electrostatic to gravitational force between the electron and proton, $(e^2/Gm_p m_e) \sim 10^{40}$, or of the radius of the universe to the radius of the electron, $[(c/H_0)/(e^2/m_e c^2)] \sim 10^{40}$, seem to be of the same order and approximately equal to the square root of the number of baryons in the observable universe:

$$\mathcal{N} = (4\pi/3)(c/H_0)^3 \times \left(3H_0^2/8\pi Gm_p\right) \sim 10^{80}. \tag{12}$$

Here e is the electron charge while m_e and m_p are, respectively, the masses of the electron and the proton.

Dirac used this "coincidence" of large numbers to formulate a "large numbers hypothesis" (LNH), essentially saying that any large (dimensionless) number that can be expressed as $A (t_0/t_e)^k$, where k and A are of order unity, t_0 is the present epoch, and $t_e = e^2/m_e c^3$ is the time taken by light to traverse the classical electron radius, varies with epoch t as $(t/t_e)^k$. Thus the LNH makes a large number of the order 10^{40} correspond to $k \sim 1$, and a number of the order 10^{80} correspond to $k \sim 2$. Dirac identified the atomic (or microscopic) system as made of atomic constants and argued that with respect to a time defined through such units, a macroscopic quantity may vary. For example, if we consider the relation between electrostatic and gravitational forces, we find that the macroscopic quantity G should vary as t^{-1}. (Other quantities in that ratio are strongly constrained by atomic physics and spectroscopy). Hence, in an expanding universe with $S \propto t^n$, with n of order unity, we should have $|\dot{G}/G| \sim H$.

This deduction from the LNH forces one to modify the Einstein equations of gravitation. Dirac proceeded to do so in a simple manner by arguing that the Einstein equations continue to hold unchanged, but in a space/time metric that is conformal to the metric used to describe atomic physics. The ratio of the two metrics $\beta = ds_{Einstein}/ds_{Atomic}$ can be a function of space/time, certainly of time. Dirac gave further arguments for determining β, partly intuitive, partly based on the LNH, and partly dictated by observations. In particular he felt it necessary

to postulate creation of new particles, either additively (i.e., in proportion to the spatial volume) or multiplicatively (in proportion to the existing mass in the region. For details, see Dirac 1973, 1974; see also Canuto & Hsieh 1978, Canuto et al. 1979; for a review, see Narlikar & Kembhavi 1980.

Perhaps the most significant prediction of these models has been the secular variation of G. The observational accuracy of lunar laser ranging, Viking radar studies in the solar system, and studies of pulsars have placed stringent observational upper limits of the order $\sim 10^{-11}$ per year on $|\dot{G}/G|$, thus making the LNH prediction untenable (Will 1993, 1998). Even if the LNH is discounted, the intriguing issue of large dimensionless numbers raised by Dirac remains.

6.3. Machian Cosmologies

Mach's principle (Mach 1893) arose from the observation that the frame of reference in which the distant stars and galaxies do not rotate happens to be a unique local frame that is inertial. As the concept of inertia and the origin of inertial forces is linked with this frame, Mach had argued that the concept of inertia itself is intimately connected with the cosmological background. This somewhat vaguely expressed idea is known as Mach's principle. Although Einstein himself was initially impressed by Mach's arguments, he later came to discount them, as they suggested action at a distance (for a historical review, see Barbour & Pfister 1995).

Gödel's (1949) demonstration referred to above showed that spinning universes in GR do not subscribe to Mach's principle. There were efforts by others, such as Sciama (1953), Brans & Dicke (1961), Hoyle & Narlikar (1964, 1966), etc., which modified GR and hence cosmology to give explicit quantitative expressions to Mach's ideas. Of these the Brans-Dicke theory played an interesting role in offering alternative predictions of the solar system tests of gravity. These prompted an upsurge of experimental techniques to make accurate measurements for distinguishing between the predictions of this theory and GR. The action principle of this theory is given by replacing the Hilbert term in GR by

$$\mathcal{A} = \frac{1}{16\pi G} \int_{\mathcal{V}} (\phi R + \omega \phi^{-1} \phi^k \phi_k) \sqrt{-g} d^4 x. \tag{13}$$

The parameter ω distinguishes the Brans-Dicke theory from GR, with the scalar field ϕ playing the role of G^{-1}. By appropriate scaling, one can show that this theory approaches GR as $\omega \to \infty$. The solar system tests have placed a lower limit of the order ~ 3000 on this parameter.

Nevertheless, the cosmological models emerging from the Brans-Dicke theory can still be significantly different from SC sufficiently early in the universe. For example, the inflationary regime can be different because of the additional terms in the action. The idea seemed to solve the graceful exit problem of the original inflationary model but ran into trouble because the distortions it produced in the cosmic microwave background were directly contradicted by the observations. Hence, a variation on the Brans-Dicke theme was explored as well as the fine

tuning of coupling constants of the scalar field. This led to several different models including those with "hyperextended inflation" (Mathiazhagan & Johri 1984). However, none of these ideas seems to have received much following in later years.

To summarize, considerations of the early and very early universe could possibly probe the differences between GR and the Brans-Dicke theory further. So far as observations of relatively recent epochs are concerned, however, the present observational constraints demand a large ω (>3000), for which there is no significant difference between GR and the Brans-Dicke theory anyway.

7. THE QUASI-STEADY STATE COSMOLOGY

In the late 1940s, Bondi & Gold (1948) and Hoyle (1948) independently proposed the steady state cosmology as an alternative to the SC. The cosmology envisaged the universe as described by the line element of Equation 1, with $k = 1$ and $S(t) = \exp Ht$, where the Hubble constant H is strictly a constant. In fact, steady state implies that the space/time has a time-like Killing vector, and that physical conditions at any epoch t are the same. One consequence of this requirement is that as the universe expands, there is creation of matter to keep its density ρ constant, the rate of creation per unit volume being $3H\rho$. The cosmology thus has no singular epoch and no hot past. Bondi & Gold believed that the entire dynamics and physics of the universe should follow from a single principle they had enunciated, namely the perfect cosmological principle, while Hoyle sought to derive the model from Einstein's field equations that contained explicit field terms to represent creation of matter.

In the 1950s and early 1960s, the steady state cosmology provided a stimulus to observers to stretch the limits of their observing technology to test the predictions of this model and to distinguish it from the SC. In the end, most cosmological tests involving discrete source populations turned out to be inconclusive, as it became clear that one first needs to understand the physical properties of the sources used for the tests before drawing unequivocal conclusions. Nevertheless the steady state theory failed on two important counts, namely the production of light nuclei (especially deuterium and helium) and the explanation of the origin of the microwave background.

The theory, abandoned in the 1970s and 1980s, was revived in a new form by Hoyle et al. (1993) and developed to some level of detail in a number of papers. These details include the basic rationale and genesis of the idea (Hoyle et al. 1993), its astrophysical and observational consequences (Hoyle et al. 1994a,b, 2000), formal theoretical structure (Hoyle et al. 1995), cosmological models (Sachs et al. 1996), and model for structure formation (Nayeri et al. 1999). We briefly summarize and assess this model, as we feel that although not studied in anything like the detail one finds for the SC, at present it is the only possible alternative in the field to which the same observational and theoretical criteria for a viable cosmology can be applied.

7.1. Broad Features of the QSSC Model

The theoretical structure and relationship to observations of this cosmology are summarized below.

1. The cosmology is based on the Machian theory of gravitation first proposed by Hoyle & Narlikar (1964, 1966). The Hoyle/Narlikar theory starts with the premise that the inertial mass of any particle is determined by the surrounding universe. In field theoretic language, the inertia is a scalar field whose behavior is determined by an action principle. As shown by Hoyle et al. (1995), the theory permits broken particle world lines, i.e., creation and destruction of matter. In the cosmological approximation of a well-filled universe, the field equations become

$$R_{ik} - \frac{1}{2}g_{ik}R + \lambda g_{ik} = -\frac{8\pi G}{c^4}\left[T_{ik} - f\left(C_iC_k - \frac{1}{4}g_{ik}C^lC_l\right)\right], \quad (14)$$

where C is the scalar field representing the inertial effect associated with the creation of a new particle, and a consequence of Mach's principle is that the constants in these equations can be related to the fundamental constants of microphysics and the large-scale features of the universe. Thus restoring c for the sake of units, we have

$$G = \frac{3\hbar c}{4\pi m_P^2}, \quad \lambda = -3\left[\frac{m_P}{\mathcal{N}}\right]^2, \quad f = \frac{2}{3}\hbar c. \quad (15)$$

Here m_P is the mass of the basic particle created, and $\mathcal{N}$ the number of such particles in the observable universe. From the above it is easy to identify m_P with the Planck mass, which makes $\mathcal{N}$ of order 10^{60} and λ of order 10^{-56} cm^{-2}. Notice that its sign is negative, i.e., it is an attractive rather than a repulsive force. The coupling constant f is positive, thus requiring the C-field stress and energy to act repulsively on matter and space because of the explicit minus sign in the stress tensor. It is assumed that the creation of a particle of mass m_P is possible provided a "threshold" is attained by the ambient C-field, namely $C_lC^l = m_P^2$. In such cases, we may have situations with $T^{ik}_{;k} \neq 0$, although the divergence of the overall right-hand side is zero.

2. The cosmological models in this theory are driven by the creation process, and it is argued that the creation does not occur uniformly everywhere, but preferentially near massive objects collapsed close to the state of a black hole. This is because the gravitational field in the neighborhood of such an object is high and permits the local value of C_lC^l to rise high enough to reach the creation threshold. The Planck particle so created is assumed to be unstable, however, and decays within a timescale of order 10^{-43} s into baryons, leptons, pions, etc., along with a release of a substantial amount of energy. The creation of matter is compensated by the creation of the C-field, and as the strength of the field rises, its repulsive effect makes the space expand rapidly

(as in the inflationary scenario), thus causing an explosive ejection of matter and energy. The origin and outpouring of very high energy in quasars, active galactic nuclei, etc., are claimed by the QSSC to be phenomena representing minicreation events like these.

In a typical minicreation event, the central object itself may break up as its gravitational binding is loosened by the growth of the negatively coupled C-field. Thus it may also happen that the central object may eject a coherent piece along the line of least resistance. The QSSC authors argue that some of the "anomalous redshift" cases (see Arp 1998, Narlikar 1989) can be explained by this phenomenon.

3. The cosmological solutions are driven by the minicreation events, each of which produces local expansions of space. The averaged effect of a large number of such events over a cosmological volume can be approximated by a homogeneous and isotropic solution of the field equations. As in the SC, the Robertson-Walker line element can be used to describe such a space/time. The work of Sachs et al. (1996) has shown that the generic solution for all three cases $k = +1, 0, -1$, is one obtained by a long-term steady expansion interspersed with short-term oscillations. For example, the scale factor for $k = 0$ is given by

$$S(t) = \exp(t/P)[1 + \eta \cos \tau(t)], \qquad (16)$$

where $0 < \eta < 1$, so that S oscillates between two finite values and $\tau(t)$ is almost like t during most of the oscillatory cycle, differing from it mostly during the stage when S is close to the minimum value. The period of oscillation Q is small compared with P. The QSSC is therefore characterized by the following parameters: P, Q, η, and z_{max}, the maximum redshift seen by the present observer in the current cycle. Sachs et al. (1996) took $P = 20Q$, $Q = 4.4 \times 10^{10}$ years, $\eta = 0.8$, $z_{max} = 5$, as an indicative set of values. The QSSC workers have argued that the cosmology is by no means tightly constrained around these values, by the various cosmological tests.

4. How is the microwave background produced in this model? The QSSC oscillations are finite with the maximum redshift observable in the present cycle at $\sim$5–6. Thus each cycle is matter dominated. The radiation background is, however, maintained from one cycle to next. Thus from the minimum-scale phase of one cycle to the next, its energy density is expected to fall by a factor $\exp(-4Q/P)$. This drop is made up by the thermalization of starlight produced during the cycle. Thus, if ϵ is the energy density of starlight generated in a cycle, and u_{max} is the energy density of the CMBR at the start of a cycle, then $\epsilon \cong 4u_{max}Q/P$. If the cycle minimum occurred at redshift z_{max}, then the present CMBR energy density would be $P\epsilon/4Q(1 + z_{max})^4$. Substituting the values of ϵ, P, z_{max} and Q we can estimate the present-day energy density of CMBR, and the result agrees well with

the observed value of $\sim 4 \times 10^{-13}$ erg cm^{-3} corresponding to temperature ~ 2.7 K.

How is the starlight thermalized? Consider the following scenario. The cooling of metallic vapors including carbon produces whisker-like particles of lengths ~ 0.5–1.0 mm, which convert optical radiation into radiation of millimeter wavelengths. Such whiskers typically form in the neighborhood of supernovae (which eject metals) and subsequently pushed out of the galaxy through pressures of shock waves. It can be shown that a density of $\sim 10^{-35}$ g cm^{-3} of such whiskers close to the minimum of the oscillatory phase would suffice for thermalization of starlight. Narlikar et al. (1997) have discussed evidence for such whiskers in different astrophysical settings.

Calculations of starlight generated per cycle show that while the thermalized radiation from previous cycles will be smoothly distributed, a tiny fraction ($\sim 10^{-5}$) will reflect anisotropies on the scales of rich clusters of galaxies in the present cycle. The angular scales for this anisotropy are estimated to be such as to generate peaks in power spectrum at $l \sim 200$ for clusters of diameter 5–6 Mpc (for details see Hoyle et al. 2000).

5. In a recent paper Burbidge & Hoyle (1998) argued that a case may be made for all isotopes to have been made in stars, including the light ones generally assumed to be of primordial origin. Of the light nuclei, the longer timescales of the QSSC allow amounts of ^{4}He to be produced in stars, sufficient for all its observed abundance to be of stellar origin. Why then do we not see a high metal content also? The reason is that in a long-timescale cosmology, the helium comes from low-mass stars, which do not reach the stage of producing metals. (In the shorter timescales of SC, the metals come from high-mass stars.) Burbidge & Hoyle (1998) have pointed out that spallation reactions of high-energy cosmic-ray protons on ^{12}C and ^{16}O nuclei can produce the isotopes ^{6}Li, ^{9}Be, ^{10}B, and ^{11}B. Modern work shows that high-energy C and O can also bombard protons and α-particles to produce these nuclei (e.g., see Vangioni-Flam et al. 1996) in the observed amounts. Stellar winds from massive stars and ejections from supernovae can produce such high-energy nuclei. Concerning ^{7}Li, apart from the HBBC nucleosynthesis, a process of galactic production has also been suggested by the recent observations of stellar abundances (Rebolo et al. 1988, Balchandran 1990, Lemoine et al. 1995). In short, there is the distinct possibility of understanding the abundances of these nuclei through astrophysical processes.

Burbidge & Hoyle have also argued that ^{3}He is produced in large quantities in dwarf stars. There are several other stars that show that most of the helium in their atmosphere is in the form of ^{3}He. A longer timescale for stellar processing is capable of yielding an ^{3}He/H ratio $\approx 2 \times 10^{-5}$ as observed. Likewise there is growing evidence of processes that can generate deuterium

in stars, e.g., in stellar flares and given a timescale of the order of 10^{11} years (see Section 9), it would not be difficult to enrich the interstellar gas with *D* to the extent observed. More measurements of the *D/H* ratio will throw light on the process of deuterium production. Indeed, if one can show that all nuclear abundances can be explained as of stellar origin and the microwave background is seen as thermalized starlight, then a major motivation for a hot big bang disappears. The link with very high-energy particle physics, including ideas on grand unification and supersymmetry, are then seen to apply to a Planck fireball produced in a typical minicreation event, rather than to a singular big bang.

6. The QSSC has been applied to the redshift-magnitude relation obtained by using type Ia supernovae. Banerjee et al. (2000) have reexamined the problem in the context of the QSSC for the data used by Perlmutter et al. (1999) for fitting the SC models, with or without the cosmological constant. As we have seen, the QSSC requires intergalactic dust in the form of metallic whiskers. This whisker population acts to produce further absorption in the light from distant galaxies and supernovae therein. Taking this effect into account Banerjee et al. (2000) fitted the QSSC model to data by taking the dust density as a free parameter. The optimized fit turns out to be better than that achieved by the best-fit SC model, including the cosmological constant as a free parameter. And the optimum whisker density turns out to be in the right range for thermalization of starlight into the microwave background.

   Earlier Banerjee & Narlikar (1999) had applied the QSSC model to the angular size redshift data on ultracompact radio sources to show a good fit. These authors, however, find that the models with $k = -1$ give a better fit than the flat models.

   Hoyle et al. (1994a) showed how a mixed population of strong and weak radio sources in the QSSC can generate the observed features of the number-count curve, without ad hoc evolutionary functions (commonly invoked in a similar fitting exercise of the SC).

7. Preliminary work on structure formation has shown (see Nayeri et al. 1999) that the pattern of filaments and voids for clusters can be generated by mini-creation events. Assuming that creation of new galaxies takes place selectively near highly dense regions, and that at the maximum density phase of a typical QSSC cycle, one can simulate the resulting distribution for 10^5–10^6 galaxies on a computer. It is observed that an initial random distribution changes over into a supercluster-void distribution after a few cycles. The two-point correlation function also tends to the power law form with the index (-1.8), as observed.

   While the different physical and astrophysical aspects of the QSSC have not been studied in anything like the depth that SC has been probed, these preliminary studies suggest that the cosmology deserves more critical attention than it has so far received.

8. WEAKNESSES OF THE QSSC

While the inventors of QSSC attribute its nonacceptance to mostly sociological factors, there are technical reasons why it has not gained popularity. The QSSC appears vulnerable on the following technical counts.

1. The fundamental idea of matter creation on which the QSSC is based is as yet ill defined and ad hoc. The fact that QSSC uses a negative energy field to circumvent the problem of energy conservation and the occurrence of singularity (present in big bang cosmology) is not a major advantage since the model for the *C*-field itself is arbitrary and untested in the lab. The QSSC needs to assume creation of particles with Planck energies that decay in Planck timescale and yet it uses concepts such as broken world lines (with end points) to describe the primary creation events. No sound quantum field theoretic foundation has been laid for these phenomena, and it is not clear that conventional notions of space/time are valid at Planck scales. In this respect the QSSC could be accused of repeating the mistake of standard big bang cosmology many times over by having untested physics to describe several small bangs instead of one big bang, even though the former are nonsingular. If this is a virtue, then the $t \lesssim t_{\text{Planck}}$ epoch in SC, around which Planck energy physics and quantum gravity holds sway, should be far more acceptable since this invokes the "tooth fairy" only once.

2. The negative energy field induces a fundamental instability in quantum theory. While it sounds plausible that the creation of matter and expansion of the region will reduce the strength of the *C*-field, no demonstration has yet been possible to illustrate this feature in any single-toy model of interacting field theory. In fact, attempts (T. Padmanabhan 1984, K. Subramanian, personal communication) have invariably shown that the instability grows in the simple interacting models. While this might merely reflect lack of ingenuity on the part of model builders, it is important that proponents of QSSC come up with at least a simple toy model in which the negative energy field exhibits a threshold behavior.

3. In the cosmological context of large-scale observations, the QSSC replaces the monotonically increasing expansion factor of SC by an oscillatory function, the envelope of which is monotonically increasing. Such a model lacks the simplicity and beauty of the original steady state model, which was based on a single principle of some elegance and power. In particular, the thermal nature of the cosmic background radiation arises due to a complex thermalization process involving iron whiskers. Most workers in the field consider this to be contrived or implausible and prefer the more elegant interpretation of this radiation as a relic of a hotter past. The strength of SC over QSSC can be easily illustrated in this case. Since the CMBR is strictly thermal at all wavelengths in SC, while it certainly should exhibit deviations from the thermal nature in QSSC, the proponents of QSSC can score over SC if they could

predict a precise deviation to be expected in CMBR. Though thermalization is not expected to be perfect in QSSC for $\lambda > 20$ cm, no systematic analysis of the spectral distortions vis-a-vis QSSC has been performed. In contrast, given the seven parameters of SC, one can make a clear and testable prediction regarding the spectral and angular distortions of CMBR, as described in Section 4.

4. The lack of predictive power in QSSC is also apparent in the case of angular distortions of the CMBR temperature. In the pre-COBE days the opponents of SC have used the lack of detection of anisotropies in MBR as a major arguing point against SC and did not bother to compute or characterize the anisotropies in alternative models. After the COBE detection of temperature anisotropies in 1992, some of these researchers have been attempting to reproduce similar results in QSSC in spite of the fact that a definite prediction of SC has been observationally verified. Proponents of QSSC have suggested (Hoyle et al. 2000) that there should exist anisotropies on the scales of superclusters and voids corresponding to $l \simeq (100–250)$. However, it must be noted that this "prediction" came much later than the corresponding results in SC and after a consensus emerged among standard cosmologists regarding the acoustic peaks in CMBR at these scales. In contrast, the acoustic peaks were genuine predictions of standard cosmology arising directly out of theoretical considerations. We have discussed earlier that the location and height of the peak in SC can be related to other cosmological parameters and can be used as an effective diagnostic of the cosmological models. A corresponding analysis in the QSSC is lacking. It is also not clear whether QSSC can produce the signature of $n \simeq 1$ power spectrum seen at large angular scales. To achieve credibility, the QSSC should make predictions of anisotropies at smaller angular scales before the observations from MAP, PLANCK and other probes become available.

5. Finally, it must be stressed that as the alternative to a better established SC, the onus of proving the superiority of QSSC lies with its proponents! A comparison with the models for alternative theories for Einstein's general relativity (GR) is illustrative. There have been probably more alternative theories to GR (see Will 1993) than to SC. But the serious proponents of the alternative GR models have always taken the trouble to make definite predictions illustrating the difference between their model and GR. In fact, the parameterized post-Newtonian formalism arose out of these attempts to be quantitative and predictive. Our definition of SC above, when we introduced a set of seven parameters for the model, was in the same spirit. Unfortunately, the fundamental ideas behind QSSC are not sufficiently well-defined to make predictions as concrete as, say, several of the alternative theories of gravity.

Similar comments can be made regarding several of the other features of QSSC, described above. Virtually all are post facto attempts to explain known

facts rather than attempts to make definite predictions observers can shoot at. In view of this, we now list possible future tests that could distinguish between these models.

9. FUTURE TESTS

In the light of what has been presented so far we may ask a specific question of both SC and QSSC. What test can be performed that could in principle disprove this cosmology? This question is in the spirit of Karl Popper's view of a scientific theory, that it should be disprovable. Thus if such a test is performed and its results disagree with the prediction of the theory, the theory is considered disproved. If the theory seeks survival by adding an extra parametric dimension, that is against the spirit of this question. On the other hand, if the prediction is borne out, our confidence in the theory may be enhanced, but the theory still cannot be considered proven.

9.1. Decisive Tests for SC

With regard to the SC we suggest the following tests, which we consider decisive in disproving or strongly discrediting the current versions of the SC.

1. Nonbaryonic dark matter: The discovery of a particle physics candidate for dark matter in the lab with evidence that it can exist with sufficient abundance in the universe will be another feather in the cap for SC. While the proponents of the QSSC will treat that particle as yet another decay product of the original Planck mass particle and introduce nonbaryonic dark matter into their models (bringing it closer to SC!), it will be difficult to convince the community of the need for alternative models after such a discovery. On the other hand, failure to find such a particle despite repeated searches will certainly cast doubts on the currently popular SC models.

2. The $\Omega_0 - h$ diagram: We have already seen how this diagram helps constrain the SC. Further observations may tighten the error bars on various parameters of the SC and thereby could even eliminate any permissible window in such a diagram. The MAP and PLANCK studies are expected to determine the parameters of the SC, along with other tests, such as the $m - z$ test. These will help in constraining the parameter space. A definitive determination of h to within a few percent will be important here.

3. The pattern of MBR temperature anisotropies: The SC makes definite predictions regarding features (such as the acoustic peak) in the MBR. These predictions will be put to test in the next few years, and if the currently allowed values can also account for the observed acoustic peak, then SC once again stands vindicated as a scientific theory. On the other hand, if these predictions are not borne out, the SC will lose credibility.

4. Blueshifts: If we find that a faint population of galaxies shows blueshifts, then the SC cannot be sustained. The QSSC on the other hand does predict such a population, namely the galaxies that are observed at the epochs close to the last maximum of the scale factor. The expected shifts are small, however, not exceeding ~ 0.1, and the galaxies showing it are expected to be fainter than 27^m. It should be noted that while finding such a population would disprove the SC, it does not prove the QSSC, it merely reports consistency with the theory. Likewise, not finding a blueshifted spectrum does not prove the SC but is consistent with it.

   There are, however, problems with such a test. The obvious selection effect that an astronomer looks for, line identifications on the short wavelength side of the observed line, works against finding a blueshift. As the continuum itself gets brightened by blueshift, the relatively weak blueshifted lines may be hard to detect against it. If one goes by the QSSC predictions, one needs to do spectroscopy with galaxies fainter than 27^m to find blueshifts, which is by no means easy.

5. Very old stars: The QSSC expects very old stars, born in the previous cycle, to be found in the galaxy. They could be low-mass ($\sim 0.5\,M_\odot$) stars just off the main sequence, which could be either in the giant stage or seen as horizontal branch stars without the helium flash, or very old white dwarfs. With ages as large as $\sim$(40–50) Gyr, these stars cannot be accommodated within the SC framework even with the cosmological constant. Their actual percentage can be estimated only after the initial mass function is well known at the low mass end.

6. Baryonic dark matter: If through studies of clusters of galaxies containing hot gas, intergalactic space containing dust, and MACHO-type microlensing observations, it is shown that the baryonic density parameter Ω_B exceeds, say, $0.02h_0^{-2}$, then the SC stands disproved, as it will have lost its one major asset, namely the ability to account for the observed D, He^3, and Li abundances. Large baryonic matter will also pose difficulties for the structure formation scenarios, which aim to explain the observed inhomogeneity of galactic matter and its large-scale motions while keeping the microwave background anisotropies at the microkelvin level.

7. Ages of stars and galaxies: Regardless of item 5 above, more precise age determination of stars in the globular clusters in the galaxy can in principle rule out many SC versions, if some ages turn out close to, say, 18 Gyr. Likewise, nuclear cosmochronology can also in principle pose problems for many SC models by turning up nuclear ages of the same order.

In addition, if one improves the age-color relationship for high redshift galaxies, one can in principle disprove many SC models by the total age criterion, i.e., look back time plus age of the galaxy exceeding the age of the universe, or by discovering fully formed mature galaxies too early in the universe.

9.2. Decisive Tests for QSSC

We next outline a few tests that hold the potential of disproving or strongly discrediting the QSSC.

1. The discovery of epochs of ultrahigh redshifts: As we have seen, the QSSC model has a maximum redshift in the present cycle. In the typical case described here, z_{max} was taken as five. There is sufficient flexibility in the model to make z_{max} somewhat higher, say up to 10–15. However, any direct evidence that the universe had passed through an epoch of much higher redshifts, say ≥ 30, would bring the credibility of QSSC into question. (Light nuclear abundances or the microwave background as known today do not constitute such evidence since these are so interpreted only within the SC framework: They have a different interpretation in the QSSC.)

    A large population of such objects is not expected at $z > 30$ in the SC either. However, a small number of such objects could possibly be explained as arising due to very large fluctuations of the Gaussian random field in SC while it is impossible to accommodate them in the QSSC in any manner.

2. Finding very old matter: Just as detection of old matter goes against the SC, so will the nondetection of such matter go against the QSSC. As the QSSC claims the observable universe to contain very old stars, dedicated searches for such objects are important to test the theory. This detection or otherwise the turn off from the main sequence at faint end and the level of subgiants in the HR diagram are a crucial test. In this connection, it is worth noting that current findings by gravitational microlensing would rule out white dwarfs 10–12 Gyr old, as they would be luminous. However, they are consistent with white dwarfs as old as 40–50 Gyr, which will be very faint.

3. Evidence for metallic whiskers: The thermalizers of the relic stellar radiation needed to produce the microwave background, viz, the metallic whiskers in interstellar and intergalactic space, hold the lifeline to the QSSC. Narlikar et al. (1997) have discussed how these are produced and distributed in space, pointing out preliminary evidence consistent with their existence. Such evidence needs to be critically examined to see if such dust indeed exists. Finding evidence for such whiskers will definitely enhance the credibility of the QSSC.

    In this connection the $m - z$ relation using type Ia supernovae out to $z > 1$ can play a crucial role. So can high redshift quasars showing substantial luminosity in the millimeter wavelengths. The finding of such quasars either means that they must be abnormally luminous in millimeter wavelengths, or that their redshifts are substantially noncosmological, a possibility referred to at the end of this section. Failing these two alternatives, the QSSC loses one of its main arguments.

4. Evidence for explosive events: The QSSC claims that the pockets of high-energy emission in the universe like the active galactic nuclei are explosive

events pouring new matter into the universe. It questions the black hole paradigm, which invokes infalling matter circulating in an accretion disc. As observational tools improve, the nuclear region can be examined more critically to see which of the two alternatives is correct. Because the SC is not related to the black hole/accretion disc paradigm, finding it (or not finding it) will not affect it seriously. However, the QSSC is more critically linked with the creation paradigm.

5. Anomalous redshifts: An issue that the QSSC could throw light on, but that is not directly related to it, is "anomalous redshifts" observation, which began to be reported on in the late 1960s (for reviews, see Burbidge 1979, Arp 1987, Narlikar 1989). Anomalies here refer to significant deviations from the Hubble velocity-distance relation, often expressed by the redshift break up of

$$(1 + z) = (1 + z_c)(1 + z_i). \tag{17}$$

Here z_c represents the cosmological redshift and z_i the intrinsic or anomalous component. Some observers claim to show anomalies in Hubble's law by showing two or more objects in close neighborhood but with different redshifts, the argument being that they both have the same z_c but differ in their intrinsic redshift components. The general view of these examples is that they confuse reality with projection effects or artifacts, or that they use wrong statistics to claim closeness of the objects. Nevertheless, while such criticism may seem more convenient than testing the counterclaim of anomaly, we have to remember that judgments of credibility or otherwise are often conditioned by the paradigm under threat, namely Hubble's law. In any case the steady accumulation of such examples over the years stresses the necessity of checking the claims thoroughly rather than ignoring them, as is commonly done.

10. CONCLUDING REMARKS

Given the various facets of SC and alternatives described in the previous pages, what could be a fair summary of the present and a reasonable prognosis for the future?

The first comment that will be universally accepted is that cosmology is poised for rapid, systematic growth in the coming years. There is a healthy interest from both observers and theoreticians in this field. This is only likely to grow in the next decade. Technology has reached a stage when automated observations on a large scale are a reality. Thus redshift surveys are expected to increase the sample of galaxies for which the angular position and redshifts are accurately known by a large factor. This will allow us to test the models for galaxy formation accurately and decisively. Analyses on a larger scale have led to claims of a periodicity for structures in the universe (Einasto 1998). Issues like this will hopefully get

settled with larger, accurate samples. Similarly, observation of CMBR and quasar absorption systems will give better constraints on the cosmological parameters.

As regards the status of SC, it only fair to say that it enjoys considerable popularity among the practicing cosmologists, and alternative models like QSSC have not been able to make any significant impact. All the same, even a strong believer in SC should find the following two features of SC disturbing.

1. The history of structure formation models is one of a series of categorical statements by the proponents, each of which had a half life of few years. In the early 1980s, it was the "unique predictions" of inflation. In the mid-1980s, after the demise of the hot dark matter model, it was the success of pure-CDM with $\Omega = 1$ to explain the universe. Within a few years both numerical simulations and Automated Plate Measurement (APM) survey results forced a new bias (which should be thought of as an acronym for basic ignorance of astrophysical scenarios) parameter into the theory. By the early 1990s, COBE conclusively disproved the $\Omega = 1$ CDM model inspired by inflation, but the practicing cosmologists heralded the COBE results as a success for inflation and introduced more free parameters in the form of cosmological constant, hot dark matter, tilted spectrum, etc. . . . Starting in the late 1990s, a model with $\Omega_\Lambda \cong 0.7$, $\Omega_{DM} \cong 0.3$ has been said to be the cure. There is, of course, nothing wrong in theoretical models being abandoned, reformulated, or improved based on observations. Nevertheless, the credibility of SC will be higher if while making their pronouncements, cosmologists learned historical lessons summarized by the oft-quoted dictum: Cosmologists are always wrong but never in doubt.

2. The current favorite among SC-ists, having $\Omega_\Lambda \cong 0.7$, $\Omega_{DM} \cong 0.3$ has a bad case of ultrafine-tuning of parameters, in the form of a cosmological constant. While it is fairly easy to come up with models in which the cosmological constant evolves with time—for an early attempt, see e.g., Singh & Padmanabhan (1988)—it is difficult to come up with a credible model in which there are no extra free parameters and in which the current value of Ω is predicted. At the same time, there is strong resistance to give up the condition $\Omega = 1$, motivated by inflation, under the pretext of avoiding fine-tuning. In fact, the current best-fit model for all the CMBR data is one with a tilted spectrum of $n = 1.4$ and $\Omega_{tot} = 1.3$ (e.g., see Tegmark et al. 2001, Padmanabhan & Sethi 2001). Likewise, the current best-fit model for supernova type Ia observations is not the one with $\Omega_{tot} = 1$. These best fit models are ignored in favor of $\Omega_{tot} = 1$ model only because of an uncritical faith in inflation. The ready acceptance of models with $\Omega_\Lambda \neq 0$ by the community suggests a general consensus that we can live with one fine-tuning but not two.

While alternative cosmologies still have a useful role to play, their major difficulty is illustrated by the QSSC model.

So far the QSSC has developed as an alternative, and its proponents have spent considerable effort in pointing out the negative aspects of SC. While this serves

as motivation, the QSSC cannot continue to survive and hope to make an impact based purely on the shortcomings of SC. In fact, most SC-ists would argue that they know what these shortcomings are and that they believe these can be addressed within the framework of the SC itself. To be taken seriously, the QSSC needs to be developed to the same level of sophisticated modeling as the SC and should make clear predictions rather than provide post facto explanations for observed phenomena. Until this is done, it is unlikely to gain the popularity the SC currently enjoys.

Observations apart, there are new concepts coming through theory also. The general theory of relativity has served cosmology well all through the century but is now being scrutinized to see how it fits within a wider framework of unification of all interactions. Quantum gravity, the loops approach of Ashtekar (1991), or the string theory approach are all being tried and it is too early to predict what will be the generally accepted outcome. Will these new approaches throw some fresh light on Mach's principle or the large numbers hypothesis? Whatever the eventual perception may be, it has to throw fresh light on the space/time singularity and the notion of the big bang. It may also substantially modify the early universe scenarios being talked about today. In conclusion we feel that, whether observationally or theoretically, our present understanding of the universe does not justify the confidence that we may even be close to the end of the quest.

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