

An Alternative to Inflation

Stefan Hollands* and Robert M. Wald†

Enrico Fermi Institute and Department of Physics

University of Chicago

5640 S. Ellis Avenue, Chicago, IL 60637, USA

March 22, 2002

Abstract

Inflationary models are generally credited with explaining the large scale homogeneity, isotropy, and flatness of our universe as well as accounting for the origin of structure (i.e, the deviations from exact homogeneity) in our universe. We argue that the explanations provided by inflation for the homogeneity, isotropy, and flatness of our universe are not satisfactory, and that a proper explanation of these features will require a much deeper understanding of the initial state of our universe. On the other hand, inflationary models are spectacularly successful in providing an explanation of the deviations from homogeneity. We point out here that the fundamental mechanism responsible for providing deviations from homogeneity—namely, the evolutionary behavior of quantum modes with wavelength larger than the Hubble radius—will operate whether or not inflation itself occurs. However, if inflation did not occur, one must directly confront the issue of the initial state of modes whose wavelength was larger than the Hubble radius at the time at which they were “born”. Under some simple hypotheses concerning the “birth time” and initial state of these modes, it is shown that non-inflationary fluid models in the extremely early universe would result in the same density perturbation spectrum and amplitude as inflationary models, without any “fine tuning”.

Issues concerning the origin of the universe and the origin of structure in the universe are among the deepest and most fundamental in science. In the absence of any theory of quantum gravity presently capable of giving a local description of phenomena at or very near the origin of the universe, it is difficult to know what questions would be most fruitful to ask, and one cannot expect more than partial answers to any questions that can be asked. Nevertheless, there is much potentially to be gained by seeking to ask and answer fundamental questions concerning the nature of the universe.

*stefan@gr.uchicago.edu

†rmwa@midway.uchicago.edu

Among the most frequently posed fundamental questions are:

- (1) Why is the universe so nearly homogeneous and isotropic on large scales, i.e., why is it so well described by a metric with Robertson-Walker symmetry?
- (2) Why is the spatial curvature of the universe so nearly zero (and perhaps exactly zero); equivalently (assuming Einstein's equation), why is the evolution timescale for our universe so much greater than the fundamental timescales appearing in particle physics?

An image that seems to underlie the posing of these questions is that of a blindfolded Creator throwing a dart towards a board of initial conditions for the universe. It is then quite puzzling how the dart managed to land on such special initial conditions of Robertson-Walker symmetry and spatial flatness. If the “blindfolded Creator” view of the origin of the universe were correct, then the only way the symmetry (and perhaps flatness) of the universe could be explained would be via dynamical evolution arguments. Now, dynamical evolution arguments—in essence, the second law of thermodynamics—successfully explain why an ordinary gas in a box will (with overwhelmingly high probability) be found in a homogeneous state if one examines it a sufficiently long time after the box was filled with the gas, even though the box may have been filled by a sloppy and careless technician who made no attempt to arrange for the gas to be homogeneous. However, in non-inflationary models of our universe, causality arguments alone would appear preclude the possibility of dynamical evolution bringing one close to Robertson-Walker symmetry on large scales if one did not start out with such symmetry. Thus, in non-inflationary models it does not appear that the homogeneity, isotropy, and spatial flatness of the universe can be explained by the same type of argument that successfully accounts for the homogeneity of a box of gas.

Our view is that the creation of the universe is fundamentally different from the creation of a box of gas. The “sloppy technician” may be a good model for the origin of a box of gas, but we see no reason to believe in the “blindfolded Creator” model of the origin of the universe. It would therefore be very surprising (and extremely unsatisfying!) if the state of the universe were to be explained in the same manner as the state of a gas in a box. *Indeed, it seems clear that rather than seeking to use the second law of thermodynamics or other dynamical arguments to explain how the universe arrived at its current state starting from arbitrary initial conditions, we should be seeking to use the (as yet to be developed) theory of initial conditions of the universe to explain how the second law of thermodynamics came into being* (see [1]). Only when we have such a theory of initial conditions will we know if there is something left to “explain” related to the above two questions.

Nevertheless, inflationary theories were developed primarily to provide a dynamical explanation of the symmetry and flatness of our universe (as well as to provide a mechanism for diluting the presence of magnetic monopoles that may have been created in the early universe). If a sufficiently large, (nearly) spatially homogeneous region has its stress energy dominated by the potential energy of a field (which thereby effectively acts like a cosmological constant), then that region will undergo an exponential expansion that will enormously increase the size of this region, isotropize it [2], and drastically reduce its spatial curvature. Inflation thereby provides a very simple and elegant dynamical explanation of the symmetry and flatness of the universe that overcomes the causality obstacles to providing such an

explanation.

However, despite its elegance, there are at least two significant shortcomings to the explanation of the symmetry and flatness of the present universe provided by inflationary theories—even if one accepts the “blindfolded Creator” view of the origin of the universe, so that a dynamical explanation of its current state is desired/needed. First, although in inflationary models the initial conditions needed to account for the symmetry and flatness of the present universe certainly seem far less “special” than in models without inflation, it seems clear that very “special” initial conditions are nevertheless needed in order to enter an era of inflation. To see this in a graphic manner, it is useful to consider a universe that eventually collapses to a final, “big crunch” singularity. As the “big crunch” is approached, it seems overwhelmingly improbable—and, indeed, in apparent blatant contradiction with the second law of thermodynamics—that the matter in the universe would suddenly coherently convert itself to scalar field kinetic energy in just such a way that the scalar field would “run up a potential hill” and remain nearly perfectly balanced at the top of the hill for a long period of exponential contraction of the universe. In other words, it seems overwhelmingly improbable that a collapsing universe would undergo an era of “deflation” just before the “big crunch”. Thus, the region of “final data space” that corresponds to a universe that did not deflate should have much larger measure than the region corresponding to a universe that did deflate. But the time reverse of a collapsing universe that fails to deflate is, of course, an expanding universe that fails to inflate. Thus, this argument strongly suggests that the region of initial data space that fails to give rise to an era of inflation has far larger measure than the region that does give rise to an inflationary era, i.e., it is overwhelmingly unlikely that inflation will occur. We do not know the measure on the dartboard used by the blindfolded Creator, so it does not seem possible to make this argument quantitatively precise. But, suppose that the probability of the dart landing on initial conditions directly giving rise to a nearly flat Robertson-Walker model without inflation were, say, $10^{-10^{10}}$ or smaller, whereas the probability of the dart landing on initial conditions leading to inflation—and, thereby, to a nearly flat Robertson-Walker universe—were, say, 10^{-10} . Then inflation would indeed successfully enhance the probability of creation of a universe that looks like our universe by a factor of $10^{10^{10}}$ or more. But could it really be said that inflation has accounted for the creation of a universe that looks like ours?

A possible way to counter the above argument is to note that one does not need the entire universe to undergo an era of inflation, but only a sufficiently large portion of it. Although the probability that a given region will inflate may be small, if this probability is non-zero and the universe is infinite (or if infinitely many universes are created), then *some* regions will inflate. Anthropic arguments can then be invoked to explain why we happen to live in a portion of the universe that had undergone an era of inflation. However, we feel that it is legitimate to ask whether arguments of this nature should be considered as belonging to the realm of science. Such arguments are based on an assumed knowledge of quantities—such as the probability measure on the blindfolded Creator’s dartboard and the probability of producing intelligent life in universes very different from ours—that we have no hope of accessing at the present time and that may well turn out to be meaningless

when we have attained a deeper understanding of nature. It is far from clear what is really being “explained” by such arguments and whether, even in principle, any nontrivial testable predictions can be made.

A second difficulty arises when one considers the details of the models that give rise to inflation. We do not find it unreasonable to postulate that in the very early universe there was an era when the energy density of the universe was dominated by the self-interaction potential energy, $V(\phi)$, of a scalar field ϕ . However, in order to have a sufficiently long era of inflation from which the universe can exit in an acceptable manner, $V(\phi)$ must be extremely flat. Additional significant constraints arise from the quantum fluctuations in energy density produced in the inflationary models (see below). Consequently, although scalar field models do exist that result in inflation—at least, with suitable initial conditions, as discussed above—one must “tune” the parameters in these models quite carefully to satisfy all of the constraints [3]. Thus, although inflationary models may alleviate the “fine tuning” in the choice of initial conditions, the models themselves create new “fine tuning” issues with regard to the properties of the scalar field.

Thus, even if one were to accept the blindfolded Creator view of the origin of the universe, it is our view that inflationary models are not very successful with regard to providing answers to questions (1) and (2) above. However, the situation changes dramatically when one considers another fundamental question:

(3) Given that the universe has nearly Robertson-Walker symmetry, how did the departures from this symmetry originate?

Here inflationary models provide a very simple, natural, and beautiful answer to this question: The departures from homogeneity arose from the quantum fluctuations of the field responsible for inflation. Although the overall amplitude of the density fluctuations produced by inflation depends upon the details of the particular model (and thus plays more the role of a constraint on inflationary models rather than a prediction of inflation), inflationary models naturally yield a so-called “scale free” spectrum of density perturbations (see below). This prediction of a scale-free spectrum has been spectacularly confirmed during the past year by high precision measurements of the cosmic microwave background [4].

The basic mechanism by which inflationary models give rise to macroscopically important fluctuations at long wavelengths can be seen by considering the simple model of a free, massless, minimally coupled scalar field, ϕ , in a spatially flat background Robertson-Walker spacetime,

$$ds^2 = -dt^2 + a^2(t)[dx^2 + dy^2 + dz^2]. \quad (1)$$

If we consider a plane wave mode of coordinate wavevector \vec{k} ,

$$\phi(t, \vec{x}) = \phi_k(t)e^{i\vec{k}\cdot\vec{x}} \quad (2)$$

then ϕ_k satisfies

$$\frac{d^2\phi_k}{dt^2} + 3H\frac{d\phi_k}{dt} + \frac{k^2}{a^2}\phi_k = 0 \quad (3)$$

where $H = a^{-1} da/dt$ is the Hubble constant. This is identical in form to the harmonic oscillator equation with a unit mass, a (variable) spring constant k^2/a^2 , and a (variable) friction damping coefficient $3H$. Consequently, when the (proper) wavelength, a/k , of the mode is much smaller than the Hubble radius, $R_H = 1/H$, the mode will behave like an ordinary harmonic oscillator, with negligible damping. On the other hand, when the wavelength is much larger than the Hubble radius, the mode will behave like an overdamped oscillator; its “velocity”, $d\phi_k/dt$, will rapidly decay towards zero and its amplitude will effectively “freeze”.

In the quantum theory of the scalar field ϕ , each mode $\phi_k = (2\pi)^{-3/2} \int \exp(-i\vec{k} \cdot \vec{x}) \phi d^3x$ acts as an independent harmonic oscillator, with Lagrangian

$$L_k = \frac{a^3}{2} [|d\phi_k/dt|^2 - \frac{k^2}{a^2} |\phi_k|^2] \quad (4)$$

where the factor of a^3 arises from proper volume element in the Klein-Gordon Lagrangian for ϕ . (Note that ϕ_k was defined using the coordinate volume element rather than the proper volume element in order to obtain this simple form for L_k .) At a fixed time t , the ground state of the oscillator defined by eq.(4) is a Gaussian wavefunction in ϕ_k , with spread given by

$$(\Delta\phi_k)^2 = \frac{1}{2a^3(k/a)} \quad (5)$$

(see, e.g., eq.(2.3.34) of [5]). Now, if the proper wavelength of the mode is much smaller than the Hubble radius, the ground state will evolve adiabatically, and eq.(5) will continue to hold at later times. At the other extreme, if the proper wavelength of the mode is much larger than the Hubble radius, the oscillator will be overdamped, and the fluctuation amplitude $\Delta\phi_k$ will remain constant with time.

It should be noted that during a “normal” era of evolution of the universe (when $P \geq 0$ —or, more generally, $P > -\rho/3$ where P is the pressure and ρ is the mass density), the Hubble radius will grow more rapidly than a , so the Hubble radius will tend to “overtake” the proper wavelength of modes. Thus, ϕ_k may evolve from an overdamped oscillator to an underdamped oscillator, but not vice-versa. On the other hand, during an era of inflation (when $P = -\rho$), the Hubble constant is truly constant, whereas a grows exponentially with t . Thus, the proper wavelength of modes will tend to rapidly overtake the Hubble radius.

The basic mechanism by which inflation produces a spectrum of density perturbations appropriate to account for the origin of structure in our universe may now be explained. In inflationary models, the modes relevant to cosmological perturbations are assumed to be “born” in their ground state at a time when their proper wavelength is much less than the Hubble radius. These modes initially evolve adiabatically (remaining in their ground state), so the precise time at which they came into existence is not important. However, during an era of inflation, their proper wavelength becomes much larger than the Hubble radius, and their fluctuation amplitude essentially freezes at the value

$$(\Delta\phi_k)^2 \sim \frac{1}{a_0^3(k/a_0)} \quad (6)$$

where a_0 is the value of the scale factor at the time the mode “crossed” the Hubble radius, i.e., at the time when

$$k/a_0 = 1/H_0 \tag{7}$$

where H_0 is the Hubble constant during the inflationary era. Now consider these modes at a later time—but early enough that all of the cosmologically relevant modes still have wavelength larger than the Hubble radius. Combining eqs. (6) and (7), we see that the fluctuation spectrum for these modes is given by

$$(\Delta\phi_k)^2 \sim \frac{H_0^2}{k^3} \tag{8}$$

which corresponds to a “scale free” spectrum¹. Note that eq.(8) differs from eq.(5) by a factor of $(a/a_0)^2$, which is enormous for the modes of interest and thereby accounts for how quantum fluctuations can have macroscopically relevant cosmological effects.

In order for the above initial fluctuation spectrum of ϕ_k to produce a corresponding initial fluctuation spectrum of the density perturbations, it is necessary that the scalar field also make a large, essentially classical contribution to the stress-energy of the universe. If it does so, then the cross-terms in the stress-energy tensor of the scalar field between the classical, homogeneous background field ϕ_0 and the quantum fluctuations of the scalar field will give rise to cosmologically relevant density perturbations. However, in this situation where there is a large background contribution to the scalar field stress energy, it is no longer possible to treat the scalar field as a test field in a fixed spacetime background; rather, one must consider the full, coupled Einstein-scalar-field system and consider the evolution of perturbations of this coupled system. This complicates the analysis considerably, but the essential aspects of the calculation and the final results remain the same as for simple case of a test scalar field given above [6], [7].

In standard inflationary models, the initially large, background, classical energy of the scalar field is provided by potential energy, with an extremely “flat” potential. The stress-energy associated with this potential provides an effective cosmological constant in Einstein’s equation, which self-consistently drives the evolution of the universe into an inflationary era. A sufficiently “slow roll” down this potential provides a sufficiently long era of inflation for the relevant modes to behave as described above, thereby producing an essentially² scale-free spectrum of density perturbations. Thus, standard inflationary models provide an elegant mechanism by which quantum fluctuations are converted into cosmologically relevant density perturbations, although, as indicated above, much of this elegance evaporates when one examines the details required to make the models work in the desired manner.

The main purpose of this paper is to point out the basic mechanism responsible for producing density perturbations in inflationary models—namely, the evolutionary behavior

¹ The normalization of the power spectrum commonly used elsewhere differs from our conventions by a factor of k^{-3} as a consequence of the use of the volume element dk/k rather than $k^2 dk$ in the inverse Fourier transform. Thus, eq.(8) corresponds to a power spectrum that is independent of k in the alternate conventions.

²The inflationary models actually predict logarithmic corrections to the scale-free spectrum that depend upon the details of the model [3], [7].

of quantum modes with wavelength larger than the Hubble radius—will operate whether or not inflation actually occurs. Therefore, it may not be necessary to assume that an era of inflation actually occurred in order to account for the origin of structure in much the same way as in inflationary models.

In the analysis of the density perturbation spectrum arising in non-inflationary models, the modes of cosmological interest have proper wavelength much larger than the Hubble radius throughout the evolutionary history of the early universe. Therefore, one must directly confront the issue of the initial state of these modes. This issue, of course, also arises in inflationary models [8], but since in inflationary models the modes at early times had proper wavelength smaller than the Hubble radius, it seems natural to assume—as we did above—that the modes are “born” in their ground state. As mentioned above, the results are then not sensitive to the precise time at which it is assumed that the modes are born. Thus, the issue of the initial state of modes has not played a central role in analyses of inflationary models, since one merely needs to assume that the modes were born in their ground state at some point prior to or during inflation.

However, in non-inflationary models, the predictions for density fluctuations will depend sensitively on assumptions about the initial conditions of the modes. The assumptions that would appear most natural concerning the time at which modes are “born” and their initial state at birth depend primarily upon one’s view of the validity of a semiclassical description of our universe. It is usually assumed that a semiclassical description will break down—and a complete theory of quantum gravity will have to be used—if one tries to describe phenomena on a spatial scale smaller than the Planck length, l_P . It is similarly assumed that a semiclassical description will break down in the description of phenomena occurring on a timescale smaller than the Planck time, t_P . Otherwise, it is normally assumed that a semiclassical description will, in general, be valid. However, it should be noted that the arguments for these views do not go much beyond the dimensional analysis given by Planck over a century ago. Furthermore, one cannot give a Lorentz invariant version of these criteria unless one also takes the view that the semiclassical description breaks down for all phenomena involving null related events, even if they are “macroscopically separated”.

In the above conventional view, a valid semiclassical description of spacetime structure, matter fields, and their quantum fluctuations at all spatial scales larger than l_P should suddenly become possible at the Planck time, t_P . In this view, it would seem natural to assume that all the modes with wavelengths greater than l_P would be instantaneously “born” at time t_P . As the universe expands and these modes attain larger proper wavelengths, new modes would then have to be continuously created at the Planck scale to “fill in” the “gap” produced by the expansion of the original modes. Now, as already indicated above, in a non-inflationary model, the modes of cosmological interest have a proper wavelength much larger than l_P at the Planck time. If it is assumed that these modes are born in their ground state at the Planck time, then the evolutionary era during which their proper wavelength remains larger than the Hubble radius will be too short to produce large enough effects to be of cosmological interest. In addition, since the relevant modes of different wavelengths are all created simultaneously, the power spectrum will remain that of the ground state (i.e.,

$(\Delta\phi_k)^2 \propto 1/k$) rather than the scale-free spectrum obtained in inflationary models.

We wish to propose here an alternative view on the creation of modes: We propose that semiclassical physics applies (in some rough sense) to phenomena on spatial scales larger than some fundamental length, l_0 , which, presumably, is of order the Planck scale or, perhaps, the grand unification scale. In this view, it would make sense to talk about a classical metric and quantum fields at times nominally earlier than the Planck time, provided that one restricts consideration to phenomena occurring on spatial scales larger than l_0 . Thus, in this view, it would be natural to treat the modes as effectively being “born” at a time when their proper wavelength is equal to the fundamental scale, l_0 . Consequently, in this view, all of the modes would, in effect, be continuously created over all time, in contrast with the view that most of the modes (including all of the cosmologically relevant ones) are created at the Planck time and the rest are continuously created at later times.

If we assume that the modes are created in their ground state, then it is easy to see that the calculation of the fluctuation spectrum for a free, massless scalar field becomes identical to the inflationary calculation sketched above, with the Hubble radius, $1/H_0$, at the time of inflation replaced by l_0 . Thus, the desired scale free spectrum of an appropriate amplitude will be obtained. It should be emphasized that to obtain this result for a scalar field in a fixed background Robertson-Walker spacetime, no assumptions need to be made concerning the detailed behavior of the scale factor $a(t)$ in the early universe.

In order to construct a non-inflationary model in which density perturbations of the desired spectrum and amplitude are produced, it is necessary to consider a situation where there is a large background stress-energy that is linearly perturbed by quantum fluctuations of the appropriate spectrum and amplitude. As a simple model, suppose that the matter in the early universe can be described on spatial scales greater than l_0 by a fluid with equation of state $P = w\rho$, where w is a constant with value in the range $0 < w \leq 1$. (The case of greatest physical relevance would presumably be $w = 1/3$, but we prefer to admit a general w in order to emphasize that our results do not depend sensitively on the details of the equation of state.) We *assume* that the universe is well described by a flat Robertson-Walker model—as we await a theory of initial conditions that might provide some kind of deeper understanding of why this is so. To analyze the density perturbation spectrum that would be arise in this model, we must quantize the perturbations of the coupled Einstein-fluid system. The required analysis of this system has been given in [7], where a Lagrangian was obtained for a gauge invariant “velocity potential” v , defined by eq.(10.43a) of that reference. If we define $\psi = v/a$ and transform from the “conformal time” variable used in [7] to proper time, the action given by eq.(10.62) of [7] corresponds in the case of a $P = w\rho$ fluid to the Lagrangian

$$L_k = \frac{a^3}{2} [|d\psi_k/dt|^2 - \frac{c_s^2 k^2}{a^2} |\psi_k|^2] \quad (9)$$

where $c_s = w^{1/2}$ denotes the speed of sound in the fluid. This is precisely the same Lagrangian as for a test scalar field discussed above, except that the sound speed, c_s , has replaced the speed of light, $c = 1$. We may therefore immediately write down the power spectrum for ψ , valid at all later times at which the modes still have wavelength larger than the Hubble

radius

$$(\Delta\psi_k)^2 = \frac{1}{2a_0^2 c_s k} \quad (10)$$

where a_0 denotes the scale factor at which the mode was created. Under the hypothesis stated above, we take a_0 to be given by $a_0 \sim kl_0$. This yields the power spectrum

$$(\Delta\psi_k)^2 \sim \frac{1}{l_0^2 c_s k^3} \quad (11)$$

The gauge invariant gravitational potential Φ of [7] (equal to the potential $-\Phi_H$ of [9] and directly related to the “gauge invariant fractional density perturbation” $\delta\epsilon/\epsilon_0$ of [7]) is given in terms of ψ by

$$\Phi_k = \frac{\sqrt{3(6w+5)} l_P a^2}{2\sqrt{2} c_s k^2} H \frac{d\psi_k}{dt} \quad (12)$$

(see eq.(12.8) of [7]). In order to evaluate $d\psi_k/dt$, we integrate the equation of motion

$$\frac{d}{dt}(a^3 \frac{d\psi_k}{dt}) = -c_s^2 k^2 a \psi_k \quad (13)$$

and use the fact that ψ_k itself is approximately constant. Substituting the background solution for a $P = w\rho$ fluid (namely $a \propto t^{2/(3w+3)}$), we obtain

$$\frac{d\psi_k}{dt} \sim \frac{a_0^3}{a^3} \frac{d\psi_k}{dt} \Big|_{t=t_0} - c_s^2 t \frac{3w+3}{3w+5} \frac{k^2}{a^2} \psi_k \quad (14)$$

where t_0 denotes the “creation time” of the mode. The first term on the right side is negligible for $t \gg t_0$ with our assumed ground state initial conditions for ψ_k . Substitution into eq.(12) and again using the background solution yields

$$\Phi_k = -\sqrt{\frac{3}{2}} \frac{\sqrt{6w+5}}{3w+5} l_P c_s \psi_k \quad (15)$$

Consequently, eqs.(11) and (15) imply that the power spectrum for modes with wavelength greater than the Hubble radius is given by

$$(\Delta\Phi_k)^2 \sim \frac{l_P^2}{l_0^2} \frac{3w^{1/2}(6w+5)}{2(3w+5)^2} \frac{1}{k^3} \quad (16)$$

This corresponds to the desired scale free spectrum of density perturbations. Furthermore, the correct amplitude is obtained³ if we choose l_0 to be of order the grand unification scale (i.e., $l_p/l_0 \sim 10^{-5}$).

³Similar results to those we have just derived can be obtained from eqs.(12.29) and (12.32) of [7], with the understanding that the initial time appearing in eq.(12.29) for a given mode is now to be taken to be the time at which $k/a_0 = 1/l_0$, rather than some fixed time that is independent of k . However, it should be noted that the initial conditions chosen in [7] correspond roughly to a ground state condition for v_k with respect to conformal time, whereas our initial conditions correspond to a ground state condition for ψ_k with respect to proper time. This makes a very important difference for the case $w = 1/3$, where the initial conditions of [7] are chosen so as to yield no effect (i.e., a power spectrum at late times equal to a ground state spectrum) whereas our initial conditions yield as large an effect for $w = 1/3$ as for other values of w .

The above fluid model of the extremely early universe is undoubtedly far too simplistic to be taken seriously as a realistic description of phenomena occurring during that era. The above hypotheses concerning the validity of a semiclassical description and the birth of modes are also undoubtedly too simplistic—although not necessarily more simplistic than conventional assumptions that would, in effect, postulate that all of the relevant modes are born in their ground state at the Planck time. Thus, the above model is not intended to represent an accurate account of the origin of density fluctuations but rather is being proposed in the spirit of an “existence proof” for robust alternatives to inflation.

In summary, we have argued that inflation does not satisfactorily “solve” the homogeneity/isotropy and flatness “problems”—nor is any other dynamical mechanism likely to give a satisfactory explanation of the homogeneity/isotropy and spatial flatness of our universe. Rather, a much deeper understanding of the nature of the birth of our universe undoubtedly will be required. On the other hand, the mechanism for producing density fluctuations in inflationary models via the dynamical behavior of quantum modes with wavelength larger than the Hubble radius provides a very simple and natural explanation for the observed departures from homogeneity and isotropy in our universe. This mechanism will operate whether or not inflation occurred, but in non-inflationary models, the results will depend crucially on one’s assumptions concerning the birth of modes. Consequently, in non-inflationary models, we are placed in a much more uncomfortable position with regard to making reliable predictions—although this does not mean that Nature would share our discomfort to the degree that She would thereby choose an inflationary model over a non-inflationary one! We have shown above that under suitable assumptions concerning the birth of modes, a density fluctuation spectrum for non-inflationary models can be obtained (without any “fine tuning”) that is indistinguishable from that of inflationary models. Thus, we have provided an alternative to inflation. However, the determination of whether this alternative is correct (or even viable) will require a much deeper understanding than we presently possess of the nature of the universe at and near its birth.

We wish to thank Bill Unruh for helping to explain to us the manner in which inflation produces density fluctuations. This research was supported in part by NSF grant PHY00-90138 to the University of Chicago.

References

- [1] R. Penrose, in *General Relativity, an Einstein Centenary Survey*, ed. by S.W. Hawking and W. Israel, Cambridge University Press (Cambridge, 1979).
- [2] R.M. Wald, *Phys. Rev.* **D28**, 2118 (1983).
- [3] P.J. Steinhardt and M.S. Turner, *Phys. Rev.* **D29**, 2162 (1984).
- [4] C. B. Netterfield *et al.*, astro-ph/0104460; C. Pryke *et al.*, astro-ph/0104490; R. Stompor *et al.*, astro-ph/0105062 (2001).

- [5] J.J. Sakurai, *Modern Quantum Mechanics*, Addison Wesley (Reading, MA, 1994).
- [6] J.M. Bardeen, P.J. Steinhardt and M.S. Turner, Phys. Rev. **D28**, 679 (1983).
- [7] V.F. Mukhanov, H.A. Feldman, and R.H. Brandenberger, Phys. Rep. **215**, 203 (1992).
- [8] J. Martin and R.H. Brandenberger, astro-ph/0012031; A. Kempf and J.C. Niemeyer, Phys. Rev. **D64**, 103501 (2001).
- [9] J.M. Bardeen Phys. Rev. **D22**, 1882 (1980).