A post-WMAP perspective on inflation

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Abstract

Recent results from the Wilkinson Microwave Anisotropy Probe have been called a corroboration, or even a confirmation, of inflation. Yet, the results include features that require, at least, a significant distortion of what is usually meant by inflation. At the same time, critics have leveled the charge that inflation is an arbitrarily pliable theory and is therefore beyond proof or disproof. This startling dissonance in attitudes toward inflation seems to have grown out of the lack of a clear framework with which to evaluate the inflationary paradigm. In this rhetorical pamphlet we reexamine the inflationary paradigm, attempt to articulate explicitly how the paradigm and its descendant models are falsifiable, and make a sober assessment of the successes and failures of inflation.

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I. INTRODUCTION

The dawn of the 21st century has indeed yielded the promised golden age of modern cosmology. The wealth of observational data from both satellites and ground-based surveys provide an increasingly refined set of tools for probing and criticizing the increasingly coherent theoretical framework of the standard cosmological model: a hot big bang evolution of a universe filled with cold dark matter, with an early period of inflation that provides flatness and homogeneity in the observable Universe and which, at the same time, provides the source of primordial density fluctuations from which all observed structure evolved.

The recent results from the first year of data from NASA’s Wilkinson Microwave Anisotropy Probe (WMAP) are a remarkable accomplishment, a tour de force of fantastic and careful analysis. The NASA press conference announcing the results of WMAP claimed that the data provides a confirmation, or at least acorroboration, of the inflationary paradigm. This last phrase, “the inflationary paradigm,” has given rise to considerable angst amongst cosmologists. The mantra that inflation is not a theory, rather it is a paradigm, has been used by enthusiasts and detractors alike. Proponents claim that inflation is a simple but powerful environment where one can study a large variety of models and answer a host of questions. Critics respond by questioning whether inflation is really science under those circumstances, and assert that inflation, as a paradigm rather than a theory, can be engineered to provide whatever result is necessary. Indeed, the claim that WMAP corroborates inflation merely confirmed the worst fears of inflation detractors: how can one confirm a paradigm that can never be disproven?

The cosmology community must surely demand that the pillars of its standard theoretical framework have firm foundations in scientific principles: providing explanations of known information, offering new predictions, and subjecting itself to falsification. Is inflation good science? Perhaps – what is clear is that the criticisms of inflation as a scientific paradigm are not entirely unjustified. We wish to lay out a set of sober thoughts regarding inflation, both pro and con. Little in this discussion will be new. Consider this a rhetorical pamphlet rather than a paper, one where we attempt to collect and organize ideas that many have expressed, to give voice to the frustrations that many physicists and cosmologists have concerning the status of inflation as sound science, and to provide another perspective with which to continue the productive debate on the subject.¹

¹With apologies to our colleagues, given the nature of this document and the familiarity of the community with the subject matter, we have included no references.
A. An Allegory

Is the inflationary paradigm good science? By this we mean is it falsifiable? Are there any principles or predictions that are inviolable? These are the stringent questions that must be asked of any scientific paradigm. But, it is worth contemplating an analogy before denouncing inflation.

Particle physics lays claim to a remarkable theoretical foundation, its Standard Model. This model, approximately thirty years old, has been tested to an exquisite degree and, by the standards of cosmology, holds up incredibly well. But, just as one can ask whether the inflationary paradigm is good science, one can as easily ask the same of the Standard Model. More accurately, we should ask whether the gauge principle is good science. Here, we view the gauge principle as the governing concept that all fundamental interactions are mediated by vector bosons that are universally coupled to fermionic matter, representing a perfectly respected gauge symmetry. This gauge principle arising out of quantum electrodynamics is the foundation for the Standard Model.

But is the gauge principle falsifiable? What firm predictions does it make? Just as for inflation, there are many models that are consistent with the paradigm, many gauge groups that may be considered, many variations on the theme. In the real world, one must take the rather cumbersome $SU(3) \times SU(2) \times U(1)$ gauge group to explain all the data. Indeed, if the data were to be different, one would modify the gauge group or add more particles to explain every anomalous feature.

One can take this analogy even further. Taken in its simplest form, the gauge principle has definite predictions. It must have massless gauge bosons for every gauge symmetry present. And while this prediction works extraordinarily well for electromagnetism, it doesn’t work for the nuclear forces. The weak gauge bosons are not massless. One cannot even directly observe the gluons. Not all gauge symmetries are explicitly, or even approximately, respected.

Direct predictions of the simplest manifestation of the gauge principle are categorically refuted by observation. A whole new system needs to be manufactured. Outrageous modifications are made to the gauge paradigm such as the addition of a fundamental scalar Higgs boson with non-universal couplings and spontaneous symmetry breaking; and a non-perturbative realization of the gauge principle must be introduced for the color force in order to bring the gauge principle into line with observations. Should one then argue that the gauge principle is garbage? That it isn’t science because one can modify it ad infinitum in order to fit, however awkwardly, with the data? And yet the gauge paradigm is considered wildly successful. Why? Is this situation different from inflation?
B. Lessons

Particle physicists would be reluctant to characterize the gauge principle as lacking the heft of real science, or being totally devoid of inviolable predictions, and therefore not falsifiable. The answers to the provocative questions raised above are that, indeed, the gauge principle does have a set of inviolable principles: an exact (but possibly hidden) gauge symmetry, gauge bosons mediating the associated interactions, and universal couplings of those gauge bosons to matter. Each of these predictions is indeed confirmed by observation. All variants of the Standard Model, however baroque, must respect these principles.

In order to put inflation on the same footing as the gauge principle, we need to enumerate a similar set of inviolable principles. Put another way, we need to identify what makes inflation so appealing that it may suffer many alterations. What are its inviolable predictions? What are its core principles? The frustration with inflation stems from the apparent scarcity of inviolable principles, thanks to the ingenuity of creative inflationary theorists, and the apparent scarcity of independent experiments with which to test the self-consistency of inflation in the conceivable future.

II. THE INFLATIONARY PARADIGM

What are the principles underlying an inflationary theory?

We start by defining the classical inflationary paradigm as: accelerated expansion of an initially marginal super-horizon (or, super-Planck, if at $t = 0$) volume, proceeding for many doubling times (order 100), and ending everywhere (or at least over an exponentially larger super-horizon volume) with thermalization and baryogenesis (sufficient for successful nucleosynthesis). Implicit in this paradigm is some driving mechanism for the accelerated expansion and the appropriate initial conditions that would lead to it. In all realizations of which we are aware, the driving mechanism is some field, usually referred to as the “inflaton.” Suitable initial conditions for the inflaton are assumed, usually on the basis that all possible initial conditions are statistically realized. General relativity (GR) is taken to be the dynamics of spacetime.

This classical paradigm, which arises out of classical field theory, must be promoted to a quantum paradigm. So long as we are interested in spacetime curvature scales much less than the Planck scale, we continue to treat gravity as classical; however, the inflaton field must be treated quantum field theoretically. Here there are two levels of complexity which we denote the semiclassical inflationary paradigm and the quantum inflationary paradigm.

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2 Also implicit has been a particular description of the vacuum state of the theory (the Bunch-Davies vacuum), extending possibly to trans-Planckian energy scales (and hence sub-Planckian length scales), although some researchers have begun to explore the robustness of this framework.
In the semiclassical inflationary paradigm one is in the perturbative regime of the quantum theory and quantum fluctuations can self-consistently be regarded as occurring against a background of the classical evolution of the inflaton field and the metric, at least over a range of length scales extending up beyond our current Hubble volume. This paradigm is the one appropriate to new inflationary and natural inflation models. Moreover, it is this paradigm that is in play whenever predictions of inflation are compared to observational data.

In the quantum inflationary paradigm, for at least some portion of the inflationary epoch, one is in the regime where backreaction of quantum fluctuations on the spacetime need to be taken into account. To do this properly, one would need to extend GR to include quantum effects. This paradigm is the one appropriate to eternal, stochastic or chaotic inflation. The progenitors of inflation have argued that the quantum paradigm is the most satisfying realization of the inflationary paradigm, especially to alleviate the tuning of initial conditions necessary to start inflation. In this scenario the Universe is bubbling with regions that are inflating. Inflation never ends everywhere; nevertheless, there are pockets that stop inflating and subsequently thermalize. According to this quantum scenario, we live in one of the thermalized regions. Inflation is therefore anthropic. Conditional probabilities for predictions are found with the condition that the thermalized region be inhabitable. The Universe is not homogeneous on the largest scales, but regions large enough to accommodate our visible Universe can be smooth enough.

The apparent simplicity of these paradigms makes inflation so attractive. Unfortunately, it also means that there are only a few generic features to characterize inflationary models of the Universe observationally or experimentally. Nevertheless, even these few ingredients do seem to have certain consequences:

A. Homogeneous, Isotropic Entropy-Filled Universe.

That the accelerated expansion of the Universe ends everywhere is implicit in the semiclassical paradigm. That it does so in the quantum paradigm is no less true, but much more subtle, incorporating generically the simultaneous truths that at any given place it eventually ends, but that it never ends everywhere, and the volume of space in which it has ended is vastly smaller than the volume in which it has not. Indeed, in this picture it is often justified only anthropically why we do not inhabit a still-inflating region. Either way, we apparently must live in a region where the energy stored in the field driving inflation, the inflaton, was converted into other more prosaic forms of energy. The vast amount of inflationary expansion is followed in all generic models by a rapid injection of entropy and its thermalization (through either reheating or preheating). This is taken to be governed
by a Lagrangian density which is independent of space-time location. It is difficult to put any measure on the predicted efficiency of this process, but the reheat temperature must be high enough to allow nucleosynthesis.

In the semiclassical paradigm, the vast inflationary expansion provides (almost) homogeneous initial conditions for entropy injection and thermalization over some large length scale. This scale may however be limited (as in $\lambda \phi^4$ theory) where, despite weak coupling ($\lambda \ll 1$) the semiclassical approximation ($\delta \rho/\rho \ll 1$) fails on sufficiently large scales. Thus, homogeneity sufficient to accommodate the semiclassical assumption over a moderate range of scales is a consequence of weak coupling.

In the quantum paradigm homogeneity seems to be an assumption that can be made self-consistently rather than a prediction. In this scenario, quantum fluctuations can be large, though inflation might be quenched wherever this happens. Models exist in which the fluctuations remain tamed.

**B. Super-Horizon Fluctuations**

The inevitable quantum fluctuations in the inflaton field will be stretched beyond the cosmic horizon and imprint themselves in the resulting energy density after reheating. Only after inflation stops and conventional big-bang evolution occurs will scales that left the horizon during inflation reenter the cosmic horizon. These fluctuations thus appear super-horizon in scale. Unfortunately, there is no minimum predicted amplitude of scalar fluctuations; their spectrum is model-dependent.

The same type of fluctuations would be produced for any light (compared to inflationary Hubble scale), non-conformally-coupled field, e.g., gravity waves. As with inflaton fluctuations, these field fluctuations will be super-horizon. However, unlike the inflaton, these fields are not expected to carry the bulk of the Universe’s energy density, and sifting for these particular signature fields may be challenging. The amplitude for super-horizon tensor (gravity-wave) fluctuations is constrained from below by the requirement that the post-inflationary reheat temperature be larger than that necessary for nucleosynthesis. In principle this constraint offers a strictly falsifiable prediction of the inflationary paradigm, though in practice the minimum amplitude is inaccessible for the foreseeable future.

**C. Other Model-Independent Predictions**

Of course, there are other predictions, such as the existence of inflaton particles that should appear at the inflationary mass scale. These particles, however, may be extremely weakly coupled to conventional matter and may be difficult to observe, even if one had
access to such energies. Nevertheless, the inflaton field cannot be completely decoupled from standard model physics. A significant amount of reheating to conventional particles requires some amount of coupling. This coupling may in principle be exploited, putting inflation strictly within the regime of particle physics, and providing another avenue for the falsification of inflation. Unfortunately, unless the inflation energy scale is very low compared to the Planck scale (e.g., near energies of $\approx 1$ TeV), this also remains an inaccessible possibility for the foreseeable future.

**III. MODEL-DEPENDENT PREDICTIONS**

Unfortunately, other predictions depend on the particular inflation model employed. As indicated earlier, the ingenuity of theorists has shown that the idea that the Universe can be homogenized with an early stage of accelerated expansion may be incorporated (with varying degrees of ease) in an overwhelmingly diverse set of models. However, we may take the predictions made by the simplest models as a guide for what is more or less natural in an inflationary model.

We can imagine a scenario where hypothetical observers know very little about observational cosmology except that the Universe is very old and filled with matter. However, they have a great deal of understanding about the rest of physics, and in particular, have been led to believe that gravitation is intimately connected with the dynamics of spacetime and that GR should govern the evolution of the Universe. In so doing, they would have realized, as have we, that the age of the Universe, as determined from the ages of planetary and meteoroidal material, is much greater than the only natural time scale of GR – the Planck time, and that the curvature scale of the Universe is much greater than the only natural length scale in GR – the Planck length. They might also have wondered where all the entropy in the Universe came from, and why, in particular, the total energy of everything they could see was much greater than the only natural mass scale in GR – the Planck mass.

Faced with these problems – the age problem, the flatness problem and the entropy problem – they might well have developed the beautiful paradigm of inflation: the idea that there was in the early history of the Universe an epoch of accelerated expansion driven by the energy density and negative pressure of the instantaneous vacuum state, which serves to flatten the Universe, vastly increase the characteristic dynamical time scale of cosmology, and fills the Universe with a relatively homogeneous and abundant “soup” of particles. In the absence of any substantial data, physicists in this world would turn to the most basic models of inflation to ascertain possible new predictions about cosmology.

The simplest versions of inflation involve a single scalar field, minimally coupled to gravity, with a potential polynomial in the field, e.g., $V = \lambda \phi^4$ where $\phi(x^\mu)$ is the inflaton
field, and $\lambda$ is small. The inflaton begins trapped in some state far away from the true vacuum, $\phi(t = 0, x) = \phi_0 \gg M_P$, where $M_P$ is the Planck mass. If $\phi_0 \ll M_P \lambda^{-1/6}$, we are in the semiclassical paradigm. The inflaton field rolls slowly down the potential as the Universe engages in accelerated expansion. Eventually, the field exits the slow-roll regime and coherently oscillates around the vacuum. This oscillation induces preheating and reheating to standard model particles, and the Universe subsequently evolves via a standard hot-big-bang model. If $\phi_0 \gg M_P \lambda^{-1/6}$, we are in the quantum paradigm. The Universe begins in a stochastically inflating state but eventually transitions into a regime where $\phi(t) \ll M_P \lambda^{-1/6}$ in some region; semiclassical behavior subsequently dominates. Evolution in this region proceeds as in the semiclassical paradigm.

A. Flat Universe

In this simplest model, inflationary expansion flattens the Universe beyond the ability of any likely experiment to discern a non-zero value for $|\Omega - 1|$. Thus, the hypothetical cosmologists would conclude that $|\Omega - 1|$ should be so small as to not be easily measurable.

One can see how this prediction can be easily avoided by looking beyond the simplest models. The original terrestrial (“old”) inflationary models, in which inflation ended via a first-order phase transition generically predicted that if we live in a single bubble of the true vacuum then the space-like hypersurfaces of constant curvature should be hyperbolic ($\Omega < 1$). (When cosmological data suggested that indeed $\Omega \simeq 0.3$, this fact was used to argue that $\Omega \simeq 0.1 - 1$ was generic.) However, first-order inflation (unless dressed up with double inflation, topologically-non-trivial manifolds, or other complexifications) fails to solve the suite of inflation-motivating cosmological problems. Moreover, if even in the simplest models, inflation can accommodate observably non-flat universes by allowing inflation to turn off at exactly the correct number of e-foldings. Of course, this just-so possibility is often viewed as unpalatable and unnatural.

B. $\delta \rho/\rho \lesssim 1$

In the semiclassical regime, for an inflationary field $\phi$ with a self-interaction potential $V(\phi)$, the amplitude of scalar fluctuations (as opposed to vector or tensor modes) is

$$\frac{\delta \rho}{\rho} \sim \frac{V^{3/2}}{V' M_{Pl}^2}.$$  \hspace{1cm} (3.1)

Specifically, to find the amplitude of fluctuations on a particular scale, we evaluate the right-hand side of Eq. (3.1) at the value which $\phi$ held when that particular scale crossed out of the apparent horizon. It might seem that this easily could be much less than unity. However,
During slow-roll, there is a relationship between $\phi$ and the number of e-foldings until the end of inflation, $N$,

$$N \sim \frac{\phi^2}{M_{Pl}^2}.$$  \hspace{1cm} (3.2)

For the model $V(\phi) = \lambda \phi^4$, Eq. (3.1) may be recast as

$$\frac{\delta \rho}{\rho} \bigg|_k \sim \lambda^{1/2} N_k^{3/2},$$  \hspace{1cm} (3.3)

where $\delta \rho/\rho|_k$ is the scalar fluctuation amplitude of a given comoving wavenumber, $k$, where $N_k$ is the number of e-foldings between when that scale left the inflationary horizon and the end of inflation. Those scales where $\delta \rho/\rho|_k > \mathcal{O}(1)$ actually probe the stochastic regime of the quantum inflationary paradigm, implying Eq. (3.3) is no longer valid.

We observe density fluctuations in the Universe over a given range of comoving scales $k$ whose $N_k \sim 100$. Equation (3.3) then implies that even though $\lambda$ may be small enough for weak-coupling to be self-consistent, density fluctuations need not be small. For $\delta \rho/\rho|_k \ll 1$, $\lambda$ must be further fine-tuned; the smaller the observed fluctuations, the more fine-tuned $\lambda$ must be. Alternatively, one may venture into so-called natural inflation models, which exploit almost-symmetries (such as pseudo-goldstone modes or flat directions in dynamically broken supersymmetry) to explain unexpectedly small density perturbations.

C. Adiabatic fluctuations

Because the energy in the field driving inflation is eventually converted into the thermal soup of radiation and matter filling the Universe, the inflaton would be converted into fluctuations in the cosmic energy density, and thence, through the dynamical response of the local geometry, into fluctuations in the metric, as well as the large-scale statistical distribution of matter in the Universe. Thus, the fluctuations would generically be adiabatic. In more complicated models of inflation, however, the fluctuations can have a non-adiabatic component.

D. Gaussian fluctuations

In the simplest inflationary models, the fluctuations arise from the excitation of independent inflaton modes. Therefore the statistics of each mode would be that of a Gaussian random field. In more complicated inflationary models, it is seen that there can be small departures from Gaussianity.
E. (Very Nearly) Equal Power on All Scales

Equation (3.1) shows that $\delta \rho / \rho$ is a function only of $V$ and $V'$. Since to realize a large number of e-folds of expansion $V(\phi)$ must be very flat, therefore the amplitude of fluctuations generated on all scales should be nearly equal. The hypothetical cosmologists would therefore conclude that the spectrum of fluctuations should be scale-free or very nearly so. In particular, unless the scale corresponding to the onset of inflation, or some other transitory event, just happens to have been stretched to a physically observable scale — less than the current horizon size yet larger than the scale on which non-linear dynamics confuses the traces of the primordial fluctuations — there should be no observable features in the primordial power spectrum that they would deduce when they some day make measurements of structure beyond their planetary system.

However, the detailed structure of the power spectrum depends on the exact form of the inflaton potential, the potential can be tuned in such a way as to provide whatever power spectrum is necessary, within some broad constraints that slow-roll inflation require. It is no wonder why many cosmologists invariably point to this feature of inflation and regard it as dangerously epicyclic. That one can tune the spectrum with an arbitrarily pliable inflaton potential to fit most any given spectrum is disturbingly unsatisfying.

IV. OBSERVATIONS AND EVALUATION OF THE PARADIGM

In our hypothetical scenario, eventually observational cosmology as we know it would be revealed. We here summarize current observations, and evaluate the inflationary paradigm in light of each piece of evidence.

1. **A homogeneous, full Universe.** Measurements of the CMB probe primarily our past light cone, and mostly the surface of last scattering. Although Occam’s razor suggests that it is highly unlikely that we just happen to live at the center (within parts per billion by volume) of a spherically symmetric inhomogeneous universe, direct observational probes of the interior of the light cone are harder to come by. However, observations of distant galaxies establish that element abundances are uniform across the Universe, suggesting that there were no large fluctuations in the energy density or baryon number at the time of primordial nucleosynthesis. Having had ample time to investigate the details of the onset and dynamics of inflation, we may well be reluctant to claim that the homogeneity and isotropy of the Universe are really great successes of inflation since the onset of inflation in any particular patch of space requires that that patch be relatively homogeneous on super-horizon scales to begin with (although once it is, inflation can vastly improve the homogeneity). Moreover, other theories
(such as variable speed of light and various braneworld scenarios) may also explain the homogeneity and isotropy, so these features are not terribly good discriminators between theories. Consistent with the classical paradigm, the visible Universe has a very large entropy, \( S \approx 10^{87} \).

2. **Super-horizon fluctuations.** The observation of acoustic peaks in the angular power spectrum of the CMB and in particular, as discussed by the WMAP team, the anti-correlation between the temperature anisotropy and the E-mode polarization at \( 1 - 2^\circ \) angular scales establishes that super-horizon scalar fluctuations exist. This observation is a true cause of celebration for the inflationary paradigm. While other theories may also predict such fluctuations, they really are a generic feature of all inflationary models. Tensor fluctuations have not yet been observed. This sets a mildly interesting limit on the inflationary energy scale, but of course far above the minimum energy scale required by nucleosynthesis.

The rudiments of the inflationary paradigm seem to hold up to scrutiny. However, as we commented, these are extremely limited, and lack a great deal of discriminatory power. What of predictions of the simplest models? How surprised would our hypothetical cosmologists be?

1. **A flat Universe.** The discovery and clear definition of the first peak in the angular power spectrum of the cosmic microwave background (CMB) established definitively that the Universe is flat or nearly so, \( \Omega \approx 1 \), in particular that \( \Omega \neq 0.3 \) as had previously been widely considered. Analysis of the WMAP observations show that \( \Omega = 1.02 \pm 0.02 \). In the simplest models of inflation, which are the only ones we are considering here, \( \Omega \) is predicted to be unity to very high precision. This fits in well with observation.

2. **An extremely homogeneous Universe.** The original discovery of the 2.7 K CMB radiation by Penzias and Wilson in 1965, was soon followed by efforts to measure any anisotropy in that background. However, it was not until 1991 that the first successful measurement of the anisotropy was made by the Cosmic Background Explorer satellite. The long delay was due to the very small amplitude of the anisotropy, only parts per \( 10^5 \). Since then many experiments have measured this anisotropy and its properties. The fine-tuning needed to achieve the observed \( \delta \rho/\rho \) would concern our hypothetical cosmologists. Because we developed inflation with the foreknowledge that \( \delta \rho/\rho \ll 1 \), we have been more prepared to accept \textit{a priori} this fine-tuning problem. As limits on \( \delta \rho/\rho \) improved through the 1980’s, the fine-tuning grew ever more severe, but it did so adiabatically, forestalling any increasing sense of concern.
3. **Adiabatic fluctuations.** All known observations are consistent with all fluctuations being entirely adiabatic in nature. As reported by WMAP the fit to their data is not improved by adding any amount of isocurvature fluctuations. This is good support for acausal generation of perturbations, and fits in very well with the simplest models of inflation. So the consistency of adiabaticity is important, but the limits on non-adiabaticity remain weak. Also a number of inflationary models have been constructed that generate non-adiabatic fluctuations.

4. **Gaussian fluctuations.** No deviations from Gaussianity have been observed in the fluctuation spectrum. The absence of any detected non-Gaussianity of the fluctuations would likely be viewed as a relief, but hardly a coup, since very nearly Gaussian distributions are rather generic due to the central limit theorem; moreover, unless one knows what non-Gaussianity to look for, finding it is really like finding a needle in a very large haystack. It is again to be noted that there exist several inflationary models that predict non-Gaussian fluctuations.

5. **Lack of equal power on all scales.** On scales characterized by $\ell$s from ten to several hundred, the angular power spectrum, as determined by many CMB experiments, and particularly by WMAP is nearly scale free. However, COBE-DMR found and WMAP has confirmed that on angular scales greater than about $60^\circ$, the two point angular correlation function of the CMB temperature fluctuations nearly vanishes. The WMAP team has argued that the best fit standard $\Lambda CDM$ model is ruled out at the 99.85% confidence level based on comparisons of the observed $C(\theta)$ with a Monte Carlo of $10^5$ realizations of the model. Mild adjustments of the model only improve that to a 99.7% exclusion. The absence of these correlations on large angular scales is a serious problem for inflation. This is not because there exist no inflationary models which accommodate it. Features in the inflaton potential, two stage inflation, just-so inflation in a compact manifold, braneworld models, etc. all may hold promise of accommodating this data. However, unless such modifications offer additional testable predictions, they are, indeed, dangerously epicyclic.

**V. CONCLUDING REMARKS**

Post-WMAP statements have been made claiming that the predictions of inflation have been confirmed, and that inflation is a successful paradigm. However, careful consideration of the meaning of the term “inflationary paradigm” suggests that such statements are, at best, imprecise. Generic predictions of the *inflationary paradigms* depend on certain
assumptions that are rarely made explicit. Granting these assumptions, the essential predictions of homogeneity and isotropy, and the existence of super-horizon fluctuations are indeed confirmed; however, only the latter is a post-inflation discovery.

Further implementation of the inflationary paradigm requires adopting a particular model. The simplest one-field inflation models have met with limited success when confronted by new data. The Universe appears spatially flat, and fluctuations are adiabatic and Gaussian. However, the fluctuation amplitude is unnaturally small and are decidedly not scale-free on the largest angular scales. While the former requires only a fine-tuning of Lagrangian parameters, the absence of large-scale power seems to demand models that are carefully designed. But, unless these new models yield testable predictions, this tack merely perpetuates the habits that inflation’s critics abhor. Do we continue to accept inflation merely because there is no better alternative?

Science is not a democratic pursuit. It only takes one contradictory fact to consign a theory to the dustbin of history, or at least to take it off its pedestal and send it back to the workshop. On the other hand, when one poses a given paradigm, it always make sense to begin with the simplest incarnation of that paradigm. The degree to which a model must be engineered to reproduce the needed data should then be factored into a reassessment of the worth of the original idea. If a theory is repeatedly faced with contradictory facts which force a reengineering, at what point does it stop being good science? If this is to be the dawn of a new era of precision cosmology, it must involve not only precise determinations of an ever increasing number of new parameters, but also precision tests of the self-consistency of our theories which permit their dispassionate evaluation.

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