Summary; Inflation and Traditions of Research

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There is a considerable spread of opinions on the status of inflationary cosmology as a useful approximation to what happened in the early universe. To some inflation is an almost inevitable consequence of well-established physical principles; to others it is a working hypothesis that has not yet been seriously tested. I attribute this to two traditions of research in physics and astronomy that come together in cosmology. The great advances of basic physics in the 20th century have conditioned physicists to look for elegance and simplicity. Our criteria of elegance and simplicity have been informed by the experimental evidence, to be sure, but the tradition has been wonderfully effective and we certainly must pay attention to where it might lead us in the 21st century. Astronomers have had to learn to deal with incomplete and indirect observational constraints on complicated systems. The Kapteyn universe — a model of our Milky Way galaxy of stars — was a product of a large effort of classifying the luminosities and modeling the motions of the stars from the statistics of star counts and star proper motions and parallaxes. This culminated in a detailed model that even offered the possibility of a “determination of the amount of dark matter from its gravitational effect” (Kapteyn 1922). But as the model was being constructed people were discovering that it must be revised, moving us from near the center to the edge of the Milky Way, where the phenomenon of stellar streaming could be reinterpreted as the circular motion of stars in the thin disk of the galaxy and the random motions of older stars in the halo. The rocky road through a vastly richer fund of observations has led to a picture for the evolution of the galaxies and the intergalactic medium during the last factor of five expansion of the universe. Many of the elements are established in remarkably close detail, but others are quite uncertain and subject to ongoing debate, elegant examples of which are to be found in these Proceedings. I think the experience has led to a characteristic tendency you might have noticed among astronomers, to ask first how a new result might have been compromised by systematic errors in the measurement, or its interpretation confused by an inadequate model. These traditions from physics and astronomy meet in cosmology, with predictable consequences for the debate on the status of inflationary cosmology.

There are astronomers who accept inflation as persuasively established, and physicists who consider inflation speculative. The latter can cite a tradition of complexity in physics, as in the study of condensed matter. Maybe it is not surprising that several of the most prominent critics of the basis for the standard cosmological model — the postulate of near homogeneity and isotropy of the galaxy and mass distributions on the scale of the Hubble length — are condensed matter physicists. I don’t understand why they are not
more influenced by the observational evidence for large-scale homogeneity, but I can fully appreciate the underlying question: could the universe really be this simple?

Einstein arrived at the homogeneity picture by a philosophical argument, that asymptotically flat spacetime is unacceptable because it is contrary to Mach’s principle. He considered this to be more convincing than the empirical evidence the astronomers could have given him about our island universe of stars and about the clustered distribution of the brighter spiral nebulae (a result, we now know, mainly of the concentration of galaxies in the de Vaucouleurs Local Supercluster). Einstein avoided all these misleading observational indications; here is an example where pure thought led to a prediction that proves to agree with demanding empirical tests, in the grand tradition of physics.

It is easy to think of examples of less successful application of pure thought, of course. Most of us would agree that the Einstein-de Sitter model is the only reasonable and elegant choice for the parameters of the Friedmann-Lemaître cosmology, because any other observationally acceptable parameter choice would imply that we flourish at a special epoch, as the universe is making the transition from expansion dominated by the mass density to expansion dominated by space curvature or a cosmological constant (or a term in the stress-energy tensor that acts like one). Maybe this is telling us that the evidence for low mass density is wrong or somehow incorrectly interpreted. But the more likely lesson is that Nature is more complicated than we had thought, and we are going to have to revise our criteria of elegance, as has happened before.

Inflationary cosmology offers an elegant way to extend the standard model for cosmic evolution back in time to conditions that cannot be described by the classical Friedmann-Lemaître model. But is the early universe really simple in the physicists’ sense, simple enough that we can hope to deduce its main properties from what we know about fundamental physics? Or might there be important elements of the complexity that astronomers are used to dealing with, and that we could hope to unravel only if we were fortunate enough to hit upon adequate guidance from the empirical evidence?

Table 1 is my summary of the pieces of evidence in hand that seem to be relevant to this issue. The characterizations in the second column follow the physical chemist Wilhelm Ostwald,¹ who felt that some physicists have a romantic temperament, eager to pursue the latest ideas, as opposed to the classical types who seek to advance knowledge by increments

¹ As represented in the novel, *Night Thoughts of a Classical Physicist* (McCormmach 1982). The title is not meant to distinguish the protagonist from a quantum physicist; at the time of the story, 1918, there was not yet a quantum theory. In Ostwald’s classification romantic physicists loved atoms and their curious properties, while classical physicists distrusted what they considered extravagant departures from conventional physics in the search for a quantum theory. Ostwald was skeptical of the kinetic theory of atoms as a basis for heat and chemistry (Jungnickel & McCormmach 1986) until the experimental success of Einstein’s theory of Brownian motion won over him and Ernst Mach (Whittaker 1953).
The Case for Inflationary Cosmology

| Evidence                                                                 | Nature       | Status         |
|-------------------------------------------------------------------------|--------------|----------------|
| Compelling elegance of inflation, and the absence of a viable alternative | a romantic test | seems well established |
| Observational case for flat space sections                              | a diagnostic, not a test? | preliminary |
| Observational case for the adiabatic CDM model                           | a diagnostic  | preliminary     |
| Tensor contribution to the CBR anisotropy                                | a classical test | open |
| Deduction of the inflaton and its potential from fundamental physics     | classical     | a wonderful dream |

from a well established basis of concepts and methods. In the table I mean by a classical test one that follows the old rule of validation by the successful outcome of tests of the predictions of a theory. By a diagnostic I mean data that can be fit by adjustment of parameters within a model for inflationary cosmology. This would turn into a classical test if we had another independent constraint on the parameters. A romantic test may point to the truth, but it lacks the beauty of an experimental check of a prediction.

The first entry in the table refers to the fact that inflationary cosmology offers an elegant remedy for very real inadequacies of the classical Friedmann-Lemaître model. This means we should pay careful attention to inflation. But those of us with classical inclinations give more weight to the successful outcome of predictions than to the ability to devise a theory to fit a given set of conditions, in what has been termed postdiction. It is impressive that no one has come up with an interesting alternative to inflation, despite the wide advertisement of the ills it cures. But one may wonder whether the significance is only that our imagination is limited.

If inflationary cosmology were falsified by a measurement that showed that space sections of constant world time have nonzero curvature, then observational evidence for flat space sections could be counted as evidence for inflation. If inflationary cosmology could be adjusted to fit the measured space curvature, then the measurement would be a diagnostic of the details of inflation, not a test. Bharat Ratra, who refined Richard Gott’s picture into a well specified model for open inflation, argues for the latter. Others argue for the former: they would take a demonstration that space curvature is not negligibly small to signify that we must abandon inflation as it is now understood and search for a better idea. Still others argue that the situation is not that simple: inflationary cosmology
is more elegant if space curvature is negligibly small, so observational evidence that this is the case would be good news, but one can work with open inflation, so the discovery of nonzero space curvature would not be bad news. It would be good if the inflation community could reach a consensus on which it is before the astronomers turn the value of space curvature into a postdiction. It is too soon to settle bets, but the astronomers seem to be getting close to a useful measurement of space curvature, as one sees in these Proceedings.

The third entry in the table refers to the striking success of the adiabatic CDM model for structure formation in fitting a broad range of observations. The original motivation for the CDM model was not inflation; the model came out of a search for a simple way to account for the small anisotropy of the thermal cosmic background radiation (the CBR). Inflationary cosmology offers an elegant explanation for the initial conditions postulated for the CDM model. This is encouraging but not a demonstration that processes directly related to inflation did provide the seeds for the CDM model. It would be no crisis if the CDM model were found to be wrong; there are other ideas for structure formation within inflation, or it could be that inflation is not directly responsible for structure formation. We would have a critical test if we had an observationally viable model for structure formation that is not consistent with inflationary cosmology, to compare to models inspired by or compatible with inflation. As things stand I think we have to count the observational evidence on how structure formed as a diagnostic of (or constraint on) the parameters of inflation, under the postulate that inflation offers the right picture for the early universe.

If the parameters are favorable inflation predicts an observable contribution to the anisotropy of the CBR from tensor fluctuations — fluctuations in the curvature of space-time. A detection of the tensor part and a demonstration of consistency with a specific model for inflation, perhaps one now under discussion, would make believers of most of us.2

As indicated in the last row of the table, the basis for fundamental physics may become so secure that it unambiguously predicts all relevant properties of the inflaton. If these properties proved to be observationally acceptable it would be a prime classical triumph. It would require a considerable advance in physics, but the advances have been prodigious.

We can look at the situation another way by asking where cosmology might have been today if we had not had the concept of inflation. If we thought we had to live with purely baryonic matter we would have been pressed to reconcile dynamical mass estimates with the baryon density required by the successful model for homogeneous production of light elements at high redshift, and we would have been pressed to find a viable model for structure formation. We don’t know how pressed; maybe we should have worked harder to save a pure baryonic universe. Nonbaryonic dark matter matter — a family of massive neutrinos — was considered before inflation. The concept of cold nonbaryonic matter

2 As the experimental success of the atomic theory of Brownian motion converted Ostwald and Mach.
grew up with inflation, but it surely would have grown as well if separated at birth, as did cosmic strings. Without inflation people would not have worked so hard to save the Einstein-de Sitter model, and negative space curvature might have been considered more favorably, but the observations would have driven us to about where we are today. Our ideas of how structure formed have been influenced by inflation, but did not depend on it. The big difference would be that, unless we hit on some alternative to inflation, initial conditions, including the Gaussian adiabatic fluctuations of the CDM model, would have been invoked \textit{ad hoc}. Inflation offers a satisfying way to fill what otherwise would be a large gap in our cosmology. Whether or not this proves to be the true explanation it certainly has helped drive the present high level of interest and research in cosmology.

Without inflation we may not have thought of searching for the graviton contribution to the CBR anisotropy, which could yield a believable positive test in the classical tradition. Other tests of inflation may show up; people are still exploring the possibilities. It also is quite conceivable that Nature will not be kind enough to give us classical tests of our ideas of what happened in the early universe; maybe inflation is a precursor of a new tradition of research by pure thought. Our rules of evidence in science have evolved since Newton claimed not to invoke hypotheses, but this would be quite a change. The record of forecasts of the end of science as we know it leads me to doubt this one, but that is for the future. These Proceedings document a wonderfully active and productive state of cosmology now, in the traditions of physics and astronomy in their classical and romantic phases.

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