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Inflationary paradigm after Planck 2013

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ABSTRACT

Models of cosmic inflation posit an early phase of accelerated expansion of the universe, driven by the dynamics of one or more scalar fields in curved spacetime. Though detailed assumptions about fields and couplings vary across models, inflation makes specific, quantitative predictions for several observable quantities, such as the flatness parameter ($\Omega_k = 1 - \Omega$) and the spectral tilt of primordial curvature perturbations ($n_s - 1 = d \ln \mathcal{P}_{\mathcal{R}} / d \ln k$), among others—predictions that match the latest observations from the *Planck* satellite to very good precision. In the light of data from *Planck* as well as recent theoretical developments in the study of eternal inflation and the multiverse, we address recent criticisms of inflation by Ijjas, Steinhardt, and Loeb. We argue that their conclusions rest on several problematic assumptions, and we conclude that cosmic inflation is on a stronger footing than ever before.

1. Introduction

Did our universe undergo a period of accelerated expansion in the early stage of its evolution? If so, does it play an important role in explaining observable features of our universe today?

We define the “inflationary paradigm” to mean that the answer to both of these questions is “yes” [1,2]. As we argue here, the inflationary paradigm draws upon well-motivated physical interactions and types of matter. The inflationary explanations for the homogeneity and the flatness of the universe can be understood in the context of classical general relativity, and even the origin of density fluctuations can be accurately described in the context of quantum field theory on a classical, curved spacetime [3], a theoretical framework that has been thoroughly studied for decades [4]. Moreover, reasoning about the behavior of fundamental scalar fields is on a stronger footing than ever, in the light of the recent observation of the Higgs boson at the LHC [5,6].

As is well known, inflation makes several generic predictions [7,8]. The observable universe today should be flat, i.e., $|\Omega_k| \ll 1$, where $\Omega_k \equiv 1 - \Omega$. There should exist primordial curvature perturbations whose power spectrum $\mathcal{P}_{\mathcal{R}}(k) \sim k^{n_s - 1}$ has a slightly tilted spectral index, $|n_s - 1| \ll 1$, typically redshifted. Unless the inflaton potential or the initial conditions are fine-tuned, the primordial perturbations should be predominantly Gaussian [9]. Modes of a given (comoving) wavelength should “freeze out” upon first crossing the Hubble radius during inflation, remain (nearly) constant in amplitude while longer than the Hubble radius, and then resume oscillation upon reentering the Hubble radius. The temporal oscillations of modes with nearby wavelengths are therefore coherent [10], giving rise to a sharp pattern of peaks and troughs in the cosmic microwave background (CMB) power spectrum. These generic predictions are consequences of simple inflationary models, and depend only on the physics at the inflationary energy scale, i.e., the energy scale of the final stage of inflation, as observed in the CMB. We will refer to these as inflation-scale predictions. To date, every single one of these inflation-scale predictions has been confirmed to good precision, most recently with the *Planck* satellite [11].

Despite these successes, Ijjas, Steinhardt, and Loeb (ISL) [12] have recently argued that the inflationary paradigm is in trouble in the light of data from *Planck*. They agree that a class of inflationary models make predictions that agree with experiment, which is how theories are usually evaluated, but they bring up a different issue. They argue that if one starts at the Planck scale with reasonable assumptions about initial conditions, the successful inflationary models are “exponentially unlikely according to the inner logic of the inflationary paradigm itself.” In this paper we argue that this is not the case by addressing each of their specific points. We will argue that their negative conclusions rely on unfounded assumptions, and can be completely avoided under what we consider to be more reasonable assumptions about the physics between the inflationary scale and the Planck scale.

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We also believe, as a matter of principle, that it is totally inappropriate to judge inflation on how well it fits with anybody's speculative ideas about Planck-scale physics—physics that is well beyond what is observationally tested. All theories of evolution begin with assumptions that are taken to be plausible, but which are usually not directly verifiable, and then the theories make predictions which can be tested against current observations. We do not reject Darwinian evolution because it does not explain the actual origin of life; we do not reject big-bang nucleosynthesis because it does not explain the homogeneous thermal equilibrium initial state that it requires; and we should similarly not even consider rejecting the inflationary paradigm because it is not yet part of a complete solution to the ultimate mystery of the origin of the universe. For us, the implications go the other way: the successes that inflation has had in explaining the observed features of the universe give us motivation to explore the speculative ideas about the implications of inflation for questions far beyond what we can observe.

If inflation occurred in the early universe, then the evidence of its own initial conditions would be effectively erased, as described by the cosmic no-hair conjecture [13]. Thus, the earliest moments of inflation, or anything that might have come before, are extremely difficult to probe observationally. Nonetheless, the inflationary framework does provide resources with which to address important open questions, such as the initial conditions at or near the Planck scale. Within that framework, important advances have been made in recent years on topics such as eternal inflation [14], the multiverse and various proposals to define probabilities [15–20], and the possible role of anthropic selection effects [21–23]. Most important, as we discuss below, the inflationary paradigm has expanded beyond what was once the dominant view, prevalent in the 1980s, which tended to focus on a single phase of "chaotic" inflation [24]. Given recent progress on both the observational and theoretical fronts, we believe that the inflationary paradigm is in far better shape than ever before.

The remainder of this paper is organized as follows. In Section 2, we discuss the implications of the Planck 2013 data. In Section 3 we discuss the initial conditions for inflation, in Section 4 we discuss the issue of predictions in the multiverse, in Section 5 we discuss what ISL call the inflationary "unlikeliness problem," and in Section 6 we discuss the possibility that the Higgs potential turns negative at large field values. We summarize in Section 7.

2. Planck 2013 data

ISL argue that the Planck 2013 data prefers single-field inflation over more complicated possibilities, and that a "plateau-like" potential looks better than other simple potentials such as power-law potentials. They argue that these facts lead to significant challenges to inflation.

The relevant observational constraints on the shape of the potential come from r, the ratio of the power spectra of tensor and scalar perturbations. For single-field models, r is proportional to the slow-roll parameter $\epsilon \equiv -\dot{H}/H^2$ and hence to $(V_{,\phi}/V)^2$. Thus small values of r require modest slope of the inflationary potential, at least in the vicinity of $\phi_I \equiv \phi(t_I)$, where t_I is the time during inflation when cosmologically relevant length scales first crossed outside the Hubble radius.[1]

On their own, the *Planck* data constrain $r < 0.12$ at the pivot scale $k_* = 0.002\ \text{Mpc}^{-1}$ at 95% CL [11]. This bound represents an impressive improvement from the WMAP9 constraint ($r < 0.38$ [25]), although it is comparable to the constraints that arise from combining WMAP data with data from the South Pole Telescope (SPT) and measurements of the baryon acoustic oscillations (BAO): $r < 0.18$ for WMAP7+SPT and $r < 0.11$ for WMAP7+SPT+BAO [26]. The *Planck* constraint is little changed if one incorporates data from SPT, BAO, the Atacama Cosmology Telescope (ACT), and large-scale polarization data from WMAP9; these combinations yield $r < 0.11$–0.13 [11].

The constraint $r < 0.12$ is low enough that the simple, single-field model with $V = \lambda\phi^4$ falls outside the 95% CL contour if one makes the usual assumptions about reheating and the thermalization energy scale after inflation. Another simple model, with $V = \frac{1}{2}m^2\phi^2$, lies at the boundary of the 95% CL contour, although it moves more squarely into the allowed region if the pivot scale corresponds to $N_* = 63$ e-folds before the end of inflation [27] rather than $N_* \leq 60$.

Thus the latest data, while certainly impressive, hardly rule out simple models with polynomial potentials, although they do constrain parameter space at the 1σ–2σ level. Nonetheless, ISL raise the conceptual question of whether plateau-like potentials are evidence against the inflationary paradigm. The main point of this paper is to argue that *even if* the final stage of inflation, as observed in the CMB, is determined definitively to occur on a plateau-like potential, the inflationary paradigm is not in trouble at all. As we discuss in the next section, the preferred scenarios might simply depart from a view about the onset of inflation that was commonly held two to three decades ago.

3. Initial conditions

In this section we will assume, for the purpose of discussing ISL's conclusions, that the observable phase of inflation—the phase which we believe produced the density perturbations that we now measure in the CMB—indeed occurred on a "plateau-like" potential. The constraints on r discussed above then require the height of the plateau $V_I \equiv V(\phi_I)$ to be no bigger than about $10^{-12} M_{\text{Pl}}^4$, where $M_{\text{Pl}} \simeq 1.22 \times 10^{19}$ GeV is the Planck scale. Because this energy density is so low, ISL argue that one needs very fine-tuned initial conditions at the Planck scale in order to have an approximately homogeneous region of Hubble size after the energy density falls to the needed value. In particular, they argue that one cannot use the simple chaotic picture $\frac{1}{2}\dot{\phi}^2 \sim \frac{1}{2}|\nabla\phi|^2 \sim V$ near $\phi \sim M_{\text{Pl}}$ to start the observable inflation, since the plateau potential energy density cannot be that high. With $\frac{1}{2}\dot{\phi}^2 \sim \frac{1}{2}|\nabla\phi|^2 \gg V \sim 10^{-12} M_{\text{Pl}}^4$ at the Planck era, ISL argue that a Hubble-sized region of homogeneity at the onset of inflation would require a region of homogeneity at the Planck scale of at least 1000 Hubble lengths.

We do not agree with this estimate, which in our view is based on false assumptions. A very plausible way to cool from the Planck scale to energy densities of order V_I, while maintaining homogeneity, is to imagine starting from a region of negative spatial curvature, $k < 0$, so that it locally resembles an open Friedmann–Robertson–Walker universe.[2] Note that $k = 0$ would be a very special case, and that regions with $k > 0$ would recollapse before reaching V_I, unless they were very close to being flat. The curvature term in the Friedmann equation, like the gradient energy $\frac{1}{2}|\nabla\phi|^2$, scales as $1/a^2(t)$, where $a(t)$ is the scale factor. The scalar field kinetic energy $\frac{1}{2}\dot{\phi}^2$ scales as $1/a^6(t)$, so the $1/a^2(t)$ terms will

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[1] Here $V_{,\phi} \equiv \partial V/\partial\phi$, where ϕ is the (scalar) inflaton field and $V(\phi)$ is its potential. We use overdots to denote derivatives with respect to cosmic time, t. The Hubble parameter is defined as $H \equiv \dot{a}/a$, where $a(t)$ is the scale factor of the Friedmann–Robertson–Walker line element.

[2] We thank Alex Vilenkin for pointing this out. Alternatively, universes with nontrivial topology, such as a torus, can also cool from the Planck scale to low energies while maintaining homogeneity [28]. In this scenario it is even possible for initial inhomogeneities to be smoothed by "chaotic mixing" [28,29].