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One-loop Pfaffians and large-field inflation in string theory

Fabian Ruehle [a,*], Clemens Wieck [b]

[a] Rudolf Peierls Centre for Theoretical Physics, Oxford University, 1 Keble Road, Oxford, OX1 3NP, UK
[b] Departamento de Física Teórica and Instituto de Física Teórica UAM/CSIC, Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain

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ABSTRACT

We study the consistency of large-field inflation in low-energy effective field theories of string theory. In particular, we focus on the stability of Kähler moduli in the particularly interesting case where the non-perturbative superpotential of the Kähler sector explicitly depends on the inflaton field. This situation arises generically due to one-loop corrections to the instanton action. The field dependence of the modulus potential feeds back into the inflationary dynamics, potentially impairing slow roll. We distinguish between world-sheet instantons from Euclidean D-branes, which typically yield polynomial one-loop Pfaffians, and gaugino condensates, which can yield exponential or periodic corrections. In all scenarios successful slow-roll inflation imposes bounds on the magnitude of the one-loop correction, corresponding to constraints on possible compactifications. While we put a certain emphasis on Type IIB constructions with mobile D7-branes, our results seem to apply more generally.

1. Introduction

Cosmic inflation is the leading paradigm to explain the anisotropies of the Cosmic Microwave Background (CMB) radiation. As inflationary theories—especially those involving super-Planckian field excitations—are highly UV sensitive, much work has been devoted to describing those theories within string compactifications. However, a study of the cosmological history in phenomenologically realistic string constructions with time-dependent four-dimensional backgrounds is technically challenging. Therefore, one usually addresses the inflationary dynamics by means of low-energy effective field theories (EFTs). Typically such an EFT has multiple cut-off scales, like the mass scales of string and Kaluza–Klein excitations and the mass scales of geometric moduli. Hence, the high energy density involved in large-field inflation necessitates a careful consistency check of all EFT limits.

Fortunately, many important aspects of this consistency can be studied in low-energy effective supergravities of different string compactifications. We wish to focus on one aspect in particular, the consistency of integrating out heavy Kähler moduli during large-field inflation. In Type IIB flux compactifications, the stabilization of the Kähler sector is particularly well understood [1,2].[1] The interplay between heavy Kähler moduli and large-field inflation in a different sector of the theory has been systematically studied in [9–15]. Here we wish to extend and generalize those analyses by including one-loop corrections to the non-perturbative superpotential in the Kähler sector, which—depending on the details of the microscopic construction—can depend on the inflaton field. This dependence, in turn, feeds back into the inflationary potential once the Kähler moduli are stabilized by these non-perturbative terms. Since in a phenomenologically viable model all moduli are stabilized we will focus in this paper on cases where the stabilizing non-perturbative term is non-vanishing at the end of inflation.

We are particularly interested in toy models with a single Kähler modulus T and an inflaton multiplet Φ from a different sector of the theory. Let us consider cases where the low-energy effective superpotential contains at least a constant piece, a quadratic term for Φ, and a non-perturbative piece to stabilize T. I.e., we consider[2]

* Corresponding author.
E-mail addresses: fabian.ruehle@physics.ox.ac.uk (F. Ruehle), clemens.wieck@uam.es (C. Wieck).

[1] While we focus here on the KKLT stabilization mechanism, we expect our results to be valid in other stabilization schemes as well, such as the ones in [3–8], as shown in [9].

[2] Note that, with this superpotential, microscopic setups that do not feature a shift symmetry for Φ do not lead to successful models of inflation. However, our

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$$K = K(T + \bar{T}, \Phi + \bar{\Phi})\,, \tag{1a}$$

$$W = W_0 + \mu\Phi^2 + A(\Phi)e^{-\alpha T}\,. \tag{1b}$$

A low-energy effective theory like this can arise as an effective theory of various string compactifications.

One example are Type IIB flux compactifications with mobile D7-branes [15–17]. There T parameterizes the volume of a four-cycle in the compact manifold Y_6 and Φ is the position modulus of a single mobile D7-brane, also wrapping a four-cycle. Moreover, W_0 and μ are sourced by components of G_3 flux on Y_6 and the non-perturbative term is sourced, for example, by a gaugino condensate on a separate stack of D7-branes. In that case α depends on the rank of the condensing gauge group. Another interesting Type IIB construction with an effective theory like (1) is given in [18,19]. There the μ-term for the inflaton is sourced by couplings to other heavy moduli which are already integrated out.[3]

In heterotic string/M-Theory and its F-Theory lift, couplings like the ones of (1) can arise, for example, from world-sheet instantons. In this case Φ is a bundle or complex structure modulus, α is given in terms of the Gromov–Witten invariants of the corresponding cycle and μ and W_0 depend on the expectation values of other heavy fields.

In [9,15] a Type IIB toy model with KKLT stabilization like the one in (1) has been extensively studied to understand the backreaction of T on the inflationary dynamics. For constant A, which is assumed in those references, the result is that, as long as W_0 and μ can be tuned independently, a large mass hierarchy between inflaton and modulus can lead to the possibility of 60 or more e-folds of slow roll inflation in agreement with the most recent CMB data. However, this ansatz implies a few non-trivial simplifications. First, the arrangement of the aforementioned four-cycles is drastically simplified, since (1) only contains a single four-cycle volume parameter. We comment on more complicated cases later on. Second, all other fields and moduli, especially the complex structure and dilaton, are assumed to be stabilized at a high scale and play no role in the discussion, which seems to be a reasonable assumption [15]. Third, depending on the details of the microscopic construction, the coefficient A in W may depend on the open-string field Φ through one-loop corrections to the instanton action. The precise form of $A(\Phi)$ is determined by the details of the geometry and the microscopic setup that leads to an inflationary universe. Technically, $A(\Phi)$ can be found by computing the Pfaffian of the one-loop diagram correcting the instanton action, which is a notoriously difficult task. This computation has only been performed explicitly in a few examples.

The most important distinction is the origin of the instanton in question. We consider the two most common cases, world-sheet instantons and gaugino condensates. For the latter, in Type IIB $A(\Phi)$ arises as open-string one-loop corrections to the gauge kinetic function on the four-cycle parameterized by T [21,22],

$$f = \alpha T + \frac{1}{4\pi^2}\log[g(\Phi)] + \dots\,, \tag{2}$$

where g also depends on expectation values of complex structure moduli. However, none of the examples where g is known explicitly features all ingredients (such as G_3 flux) necessary to realize large-field inflation. The one-loop Pfaffian for Euclidean D-brane instantons, as a function of brane position moduli, has been studied in Type II/F-theory in [23–27], cf. also the earlier discussions in [28,29]. In heterotic string theory the relevant references include [30–34]. Here the Pfaffians have been shown to yield homogeneous polynomials in complex structure and bundle moduli. Furthermore, the authors of [35–37] have shown that for both types of instantons the one-loop correction, in terms of brane moduli, can be found using purely closed-string methods. These can be used even in more complicated setups than those considered in [21,22]. Moreover, in [38–41] the authors study setups where one-loop Pfaffians generate the leading-order inflaton potential.

The rest of this paper is structured as follows. In Section 2 we discuss the possibility that $A(\Phi)$ is a polynomial function. We discuss the string theory backgrounds that produce the corresponding low-energy EFT, and address the consistency of integrating out T in these cases. In the resulting inflationary EFT we derive parameter bounds that constrain possible compactifications and depend on the degree of the polynomial. In Section 3 we discuss the possibility that $A(\Phi)$ is exponential or periodic, cases known to arise in Type IIB models with gaugino condensates and mobile D7-branes. We repeat the same analysis as in the polynomial case to study the viability of inflation. Moreover, we hint at interesting CMB signatures induced by modulations of the inflaton potential through the one-loop Pfaffian. Finally, we conclude in Section 4.

2. Polynomial Pfaffians

2.1. Motivation

Let us start by motivating how polynomial Pfaffians arise in string theory, following [26,42]. In the case of Type IIB, such instantons arise from Euclidean D3 (ED3) branes that wrap an internal four-cycle. In the M-theory lift, this corresponds to Euclidean M5-branes wrapping vertical divisors that are elliptic fibrations over a divisor in the base of a Calabi–Yau four-fold. In the corresponding F-theory description, the elliptic fiber is shrunk and the Euclidean M5-branes correspond to ED3-branes. Non-perturbative superpotentials arise from the intersection of the four-cycle wrapped by the ED3-branes with the GUT divisor. The moduli Φ are ED3- and D7-brane moduli in this setup, and here we focus on the D7-brane moduli. If a heterotic dual exists, the Pfaffians arise from world-sheet instantons on a curve whose volume is governed by the Kähler parameter T. The relevant moduli Φ are in this case bundle and complex structure moduli, cf. [26,32–34]. The one-loop Pfaffian is then a homogeneous polynomial (or a product of homogeneous polynomials) to some power. In the examples of [26,32] there is a single polynomial to the fourth power, and it was speculated that the power to which the polynomial is raised is linked to the number of zero modes of the fermionic differential operator from which the Pfaffian arises. Interestingly, as we shall see later, the results and implications for inflation differ depending on this power.

A full analysis of the entire moduli space including all dynamics is, so far, impossible due to a lack of explicit expressions for the Kähler potentials and computer power. Hence, we work under the assumption that there is a separation of scales such that some moduli have already been stabilized and integrated out at some higher scale. We treat those as effective constants and minimize the potential in terms of the lightest moduli that remain as dynamical parameters. We thus make the following ansatz for the superpotential,

$$W = W_0 + A_0\left(\sum_{m=0}^{2n}\delta_m\Phi^m\right)e^{-\alpha T} + \mu\Phi^2\,, \tag{3}$$

where the constants W_0, δ_m, and μ of the effective theory are given in terms of products of vacuum expectation values of heavy fields. In the following we use the notation

results do not depend on the precise form of $W(\Phi)$, as long as the inflationary EFT features super-Planckian field excitations.

[3] See, however, [20] for a discussions of the problems that arise when μ is tuned to a small value.