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Ultra slow-roll inflation demystified

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ABSTRACT

Ultra-slow-roll (USR) inflation is a new mode of inflation which corresponds to the occasions when the inflaton field must traverse an extremely flat part of the scalar potential, when the usual slow-roll (SR) fails. We investigate USR and obtain an estimate for how long it lasts, given the initial kinetic density of the inflaton. We also find that, if the initial kinetic density is small enough, USR can be avoided and the usual SR treatment is valid. This has important implications for inflection-point inflation.

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1. Introduction

Cosmic inflation is an organic component of the concordance model of cosmology. It is a period of exponential expansion in the early Universe, which determines the initial conditions for the subsequent Hot Big Bang cosmology. In particular, it makes the Universe spatially flat, large and uniform but also provides the necessary deviations from perfect uniformity in the form of the primordial curvature perturbation, which accounts for the eventual formation of the large scale structure. Typically, inflation is modelled through the inflationary paradigm, which suggests that the Universe undergoes inflation when dominated by the potential density of a scalar field (inflaton). This potential density remains roughly constant during inflation. As a result, the generated curvature perturbation is almost scale-invariant, as suggested by observations. In order to keep the potential density roughly constant, the variation of the field must be very small throughout inflation. Because the inflaton's equation of motion is the same as a body rolling down a potential slope subject to friction, we need this roll to be slow for the inflaton, in field space, so as to keep the potential density roughly unchanged. Thus, in the inflationary paradigm, the inflaton undergoes slow-roll (SR) during inflation. Indeed, the latest CMB data favours single-field slow-roll inflation [1].

The SR solution is an attractor [2] as long as the potential is flat enough to support it. However, it was recently realised that SR may end not only when the potential becomes steep and curved, as is for the end of inflation, but also when it suddenly becomes extremely flat, too flat for the regular SR assumptions to apply. In this case, the system engages in so-called ultra slow-roll (USR) inflation. This new mode of inflation has been hitherto unknown. It can have a profound impact on inflationary observables, so it must be taken into account. However, even though diagnosed, USR has not been fully understood, with most of its dynamics traced numerically. In this letter, we attempt to demystify USR and provide a conceptual understanding of its dynamics. Ignoring USR can lead to important miscalculations of inflationary observables.

USR arises when the potential becomes extremely flat, so much so that, SR would force the kinetic density of the field to reduce faster than it would if the field were in free-fall $\rho_{\rm kin} \equiv \frac{1}{2}\dot{\phi}^2 \propto a^{-6}$, which of course cannot happen. Thus, the system departs from SR and the field engages in USR, during which the kinetic density decreases as in free-fall, until the system can get back to SR, when the decreasing $|\ddot{\phi}|$ catches up with the slope of the potential $|V'|$, or until inflation ends, e.g. by a phase transition. Note that, even though the slope is very small, we still have potential domination $V > \rho_{\rm kin}$ so inflation continues. USR was first investigated in Ref. [3], which was followed by Refs. [4,5] and recently by Ref. [6]. In Refs. [3] and [5] a constant potential is assumed, which cannot exhibit SR. In Ref. [4] it was shown that USR is not an attractor solution and the system departs from it as soon as the conditions which enforce USR allow it. But which conditions are these?

In this letter we explore this question. To obtain an insight of the dynamics of USR, we study USR in linear inflation and then generalise our findings for an arbitrary inflation model. We particularly consider inflection-point inflation because it can lead to USR. It is fair to say that the community seems little aware of USR, so the hope is that our treatment may be revealing of USR's nature. This is a particularly acute problem in models of inflection-point inflation, where a region of USR exists around the inflection point. In USR this region is traversed in a moderate number of e-folds. However, were SR assumed, this number would grow substantially. As inflationary observables are determined by the correct number

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of e-folds, this can have profound implications on inflationary predictions and on the viability of inflection-point models.

We use natural units, where $c = \hbar = 1$ and $8\pi G = m_P^{-2}$, with $m_P = 2.43 \times 10^{18}$ GeV being the reduced Planck mass.

2. Ultra-slow roll inflation

To explore USR inflation, we will look closely at the Klein–Gordon equation of motion of the canonical homogeneous inflaton field ϕ:

$$\ddot{\phi} + 3H\dot{\phi} + V' = 0\,, \tag{1}$$

where $H \equiv \dot{a}/a$ is the Hubble parameter (with a being the scale factor) V is the scalar potential and the dot {prime} denotes derivative with respect to the cosmic time {the inflaton field}. We name each term of the above as the acceleration, the friction and the slope term respectively. We also employ the flat Friedman equation during inflation, when the Universe is dominated by the inflaton field:

$$3H^2 m_P^2 = \frac{1}{2}\dot{\phi}^2 + V\,. \tag{2}$$

We define two slow-roll parameters

$$\epsilon \equiv -\dot{H}/H^2 \tag{3}$$

and

$$\epsilon_2 \equiv \frac{\dot{\epsilon}}{\epsilon H} = -6 - \frac{2V'}{H\dot{\phi}} + 2\epsilon = \frac{2\ddot{\phi}}{H\dot{\phi}} + 2\epsilon\,, \tag{4}$$

where we have employed Eqs. (1) and (2). It is easy to show that

$$\epsilon = \frac{3}{2}(1+w)\,, \tag{5}$$

where w is the barotropic parameter of the homogeneous inflaton field, given by

$$w = \frac{\rho_{\rm kin} - V}{\rho_{\rm kin} + V}\,, \tag{6}$$

where $\rho_{\rm kin} \equiv \frac{1}{2}\dot{\phi}^2$. For inflation we need $w < -\frac{1}{3}$, which means $V > 2\rho_{\rm kin}$. From Eq. (5), we see that inflation (accelerated expansion) occurs when $\epsilon < 1$.

Now, in the usual SR, the acceleration term in Eq. (1) is negligible, so the latter becomes

$$3H\dot{\phi} \simeq -V\,, \tag{7}$$

which shows that the friction term is locked to the slope term. In this case, Eq. (4) becomes

$$\epsilon_2 = -2\eta + 4\epsilon\,, \tag{8}$$

where the usual SR parameters are

$$\epsilon \simeq \epsilon_{\rm SR} \equiv \frac{1}{2}m_P^2\left(\frac{V'}{V}\right)^2 \quad \text{and} \quad \eta \equiv m_P^2\frac{V''}{V}\,. \tag{9}$$

During SR, $\epsilon, |\eta| \ll 1$, which means that $|\epsilon_2| \ll 1$.

However, if the potential suddenly becomes extremely flat, the slope term in Eq. (1) may reduce drastically, which means that it virtually disappears. The equation is then rendered

$$\ddot{\phi} + 3H\dot{\phi} \simeq 0\,, \tag{10}$$

which shows that the friction term is now locked with the acceleration term. In this case, Eq. (4) becomes

$$\epsilon_2 = -6 + 2\epsilon\,. \tag{11}$$

During inflation $\epsilon < 1$, which means $|\epsilon_2| \approx 6$. Thus, if during inflation, the potential becomes suddenly very flat, $|\epsilon_2|$, which is initially small grows to larger than unity, SR is applicable no-more and a period of USR begins.

Intuitively, one can understand this as follows. If we are in SR but the slope $|V'|$ reduces drastically, it initially drags with it the friction term, by virtue of Eq. (7). This decreases the value of $|\dot{\phi}|$, i.e. the kinetic density $\rho_{\rm kin} = \frac{1}{2}\dot{\phi}^2$, but this value cannot decrease arbitrarily quickly. The fastest it can decrease is $\rho_{\rm kin} \propto a^{-6}$, which we call free-fall because it corresponds to a field with no potential density $V = 0$, such that its equation of motion is Eq. (10). Therefore, if the kinetic density of SR is forced (by the decreasing slope) to reduce faster than free-fall then the system breaks away from SR. In SR the acceleration term is negligible, because it is very small, compared to the friction and slope terms, which are locked together as shown in Eq. (7). However, if the slope reduces drastically and drags the friction term with it, they both become small too and eventually comparable to the acceleration term. So all three terms in Eq. (1) are comparable. When this happens, the friction term changes allegiances and becomes locked with the acceleration term, resulting in USR.

Now, once in USR, the field becomes oblivious of the potential, as demonstrated by Eq. (10). This is similar to the kination period of quintessential inflation models [7,8] but there is a crucial difference. In kination, the Universe is dominated by $\rho_{\rm kin}$, while in USR inflation, we still have potential domination and $V > \rho_{\rm kin}$. Being oblivious to the potential, the inflaton field can even climb up an ultra-shallow V [4]. Indeed, when the system enters the USR regime, it "flies over" the flat patch of the potential, sliding on its decreasing kinetic density. In that sense, the term ultra-SR is actually a misnomer, because the field rolls faster than it would have done if SR were still applicable over the extremely flat region.

Indeed, if $|V'|$ decreases to almost zero, so does $\epsilon_{\rm SR}$. In SR the number of elapsing e-folds is

$$\Delta N = \frac{1}{m_P}\int_{\phi_1}^{\phi_2} \frac{{\rm d}\phi}{\sqrt{2\epsilon_{\rm SR}}}\,, \tag{12}$$

which increases substantially if $\epsilon_{\rm SR}$ becomes extremely small. In contrast, in USR ϵ does not decrease too much, so we have $\epsilon_{\rm SR} \ll \epsilon < 1$. The number of elapsing e-folds is given in general by

$$\Delta N = -\int \frac{{\rm d}H}{\epsilon H} \tag{13}$$

and in USR it can be much smaller compared to SR if $\epsilon_{\rm SR} \ll \epsilon$. Thus, when considering an inflation model that results in periods of USR, but only SR is assumed, there is a danger of overestimating the number of e-folds it takes for the field to roll down.

It is evident that USR depends on having substantial kinetic density, which cannot decrease faster than free-fall. However, if one begins inflation at the extremely flat region with very small kinetic density, then SR may be attained, quickly, even immediately. Now, the initial conditions for inflation are shrouded by the no-hair theorem, which renders them academic, because all memory is lost once the inflationary attractor is reached. Thus, provided inflation begins comfortably before the cosmological scales exit the horizon, the initial conditions of the inflaton field can be taken to correspond to kinetic density small enough to avoid USR despite an extremely flat scalar potential. This can rescue inflation models such as inflection-point inflation, which may have problems with USR. To quantify how small the initial kinetic density needs to be, we first investigate linear inflation.

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