Spectral tilt in A-term inflation

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Recently in hep-ph/0605035 and hep-ph/0608138 we have shown that primordial inflation can be embedded within the Minimal Supersymmetric Standard Model, while providing the right amplitude for the density perturbations and a tilted spectrum which matches the current data. In this short note we show that the model predicts a range of spectral tilt, $0.92 \leq n_s \leq 1$, depending on deviation from the saddle point condition. The spectral tilt saturates the lower limit when the saddle point condition is met. On the other hand the upper limit can be achieved for a slight deviation towards the point of inflection. The running of the spectral tilt remains small, and the amplitude of the temperature anisotropies remains in the correct observational regime.

I. INTRODUCTION

Recently in two Refs. \textsuperscript{1, 2}, we demonstrated that the Minimal Supersymmetric Standard Model (MSSM) has all the ingredients to give rise to a successful inflation (see also \textsuperscript{13}). Interestingly the inflaton belongs to the MSSM, i.e. the flat directions of the MSSM \textsuperscript{1}. In \textsuperscript{1}, the inflaton candidates were the two flat directions, $LLe$ and $udd$, where $L$ stands for the left-handed sleptons, $e$, the right-handed sleptons and, $u$, $d$ stand for the right handed squarks (of the up- and down-type respectively).

On the other hand in Ref. \textsuperscript{2}, the inflaton was $NH_u L$, the right handed sneutrino, Higgs and the left handed slepton, respectively. This is an extension of the MSSM which includes Dirac neutrinos with masses in the correct range to explain the atmospheric neutrino anomaly.

The difference between the two models is; that both $LLe$ and $udd$ flat directions are lifted by the non-renormalizable superpotential terms (of order $n = 6$) which are suppressed by the Planck scale, $M_P$, while $NH_u L$ is lifted by the tiny neutrino Yukawa couplings.

There are many advantages of the MSSM inflation, first of all the inflaton is not an ad-hoc gauge singlet from the hidden sector as often assumed in the literature \textsuperscript{2}. Secondly, the inflaton couplings to the MS(SM) are known, therefore, reheating and thermalization can be understood consistently within the framework of supersymmetry \textsuperscript{6}. The final reheat temperature is sufficiently low to avoid any problem with thermal and/or non-thermal gravitinos \textsuperscript{10}. The model is insensitive to supergravity corrections and also does not rely on super-Planckian VEVs \textsuperscript{3}. The moduli problem can also be avoided all together, for all the detailed discussion, see \textsuperscript{3}.

Although, the scale of inflation is relatively small, $H_{inf} \sim 1 \text{ GeV}$, the model produces remarkably large number of e-foldings of inflation. The slow roll inflation is preceded by a phase of inflation where self-reproduction dominates due to quantum fluctuations \textsuperscript{11}. During the slow roll, the total number of e-foldings is found to be $N_e \sim 1000$. Not all the e-foldings of inflation is required to explain the temperature anisotropies seen in the sky \textsuperscript{12}, the only relevant number of e-foldings, which normalizes the COBE amplitude is nearly $N_{COBE} \sim 50$ in our case \textsuperscript{11, 2}. The details of this finding depends on thermal history of the universe, see for instance \textsuperscript{13}.

In this short note, we wish to highlight that the model properties have become even more richer, especially, the spectral tilt is bounded from below and above if the predictions of inflation are maintained. The range of spectral tilt is given by

$$0.92 \leq n_s \leq 1.$$ \hfill (1)

The lower limit is saturated for an exact saddle point behavior, while the upper limit is allowed as long as sufficient inflation is obtained, which is of the order of $N_{COBE} \sim 50$ in our case.

In section 2, we recall some of the important results of a saddle point inflation, in section 3, we describe a slight deviation from the saddle point and discuss the spectral tilt and the running of the spectrum. We also comment on the amplitude of the scalar metric perturbations.

II. SADDLE POINT INFLATION

Let us consider the potential in general, for the radial part of a flat direction, $\phi$,

$$V = \frac{1}{2} m_{\phi}^2 \phi^2 - A \frac{\lambda_n \phi^n}{n M_P^{n-3}} + \frac{\lambda_n^2 \phi^{2(n-1)}}{M_P^{2(n-3)}},$$ \hfill (2)

where $A$ is a positive number, $m_{\phi} \sim \mathcal{O}(1) \text{ TeV}$, $\lambda_n \sim \mathcal{O}(1)$. Within MSSM all the flat directions are lifted by the non-renormalizable operator, $n \leq 9$. The renormalizable potential is denoted by $n = 3$. The flat direction inflaton $NH_u L$ belongs to $n = 3$, while $LLe$, $udd$ correspond to $n = 6$.

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\textsuperscript{1} MSSM has many gauge invariant flat directions made up of squarks and sleptons, which preserve $R$-parity at the renormalizable level, for a review see \textsuperscript{4}.

\textsuperscript{2} See Ref. \textsuperscript{3} for other attempts of embedding inflation with gauge invariant SUSY flat directions, where multiple flat directions assisting inflation similar to that in Refs. \textsuperscript{6}.
When the condition\(^3\)
\[
A = \sqrt{8(n-1)m_\phi},
\]
is satisfied, then there exists a saddle point at
\[
\phi_0 = \left(\frac{m_\phi M^n}{\lambda \sqrt{2n-2}}\right)^{1/(n-2)},
\]
such that \(V'(\phi_0) = V''(\phi_0) = 0\). At this point we have
\[
V(\phi_0) = \frac{(n-2)^2}{2n(n-1)}m_\phi^2\phi_0^2,
\]
and in its vicinity
\[
V(\phi) = V(\phi_0) + \left(\frac{1}{3!}\right)V'''(\phi_0)(\phi - \phi_0)^3 + \ldots,
\]
where
\[
V'''(\phi_0) = 2(n-2)^2m_\phi^2\phi_0^2.
\]
Hence there is a plateau where the potential is very flat and inflation is driven by \(V'''(\phi_0)\).

The Hubble expansion rate during inflation is given by
\[
H_{\text{inf}} = \frac{(n-2)}{\sqrt{6n(n-1)}} \frac{m_\phi \phi_0}{M_P}.
\]

When \(\phi\) is very close to \(\phi_0\) the first derivative is extremely small, and we are in a self-reproduction (or eternal inflation) regime where quantum diffusion is dominant. But eventually classical friction wins and slow roll begins at \(\phi \approx \phi_{\text{self}}\),
\[
(\phi_0 - \phi_{\text{self}}) \approx \frac{m_\phi \phi_0^2}{M_P^2}^{1/2} \phi_0.
\]
The equation of motion for the \(\phi\) field in the slow roll approximation is given by:
\[
3H_{\text{inf}}^2 \dot{\phi} = -\frac{1}{2} V'''(\phi_0)(\phi - \phi_0)^2.
\]

Inflation ends when either of the slow roll parameters, \(\epsilon \equiv (M_P^2/2)(V'/V)^2\) or \(\eta \equiv M_P^2(V''/V)\), becomes \(\mathcal{O}(1)\).

It happens that \(|\eta| \sim 1\) at \(\phi_{\text{end}}\), where
\[
(\phi_0 - \phi_{\text{end}}) \sim \frac{\phi_0^3}{4n(n-1)M_P^2}.
\]

We can estimate the total number of e-foldings during the slow roll phase, from \(\phi\) to \(\phi_{\text{end}}\),
\[
N_e(\phi) = \int_{\phi}^{\phi_{\text{end}}} \frac{H_{\text{inf}}d\phi}{\dot{\phi}} \approx \frac{\phi_0^3}{2n(n-1)M_P^2(\phi_0 - \phi)}.
\]

where we have used Eq. (10). The total number of e-foldings in the slow roll regime is then found from Eq. (13),
\[
N_{\text{tot}} \approx \frac{1}{2n(n-1)}\left(\frac{\phi_0^2}{m_\phi M_P}\right)^{1/2}.
\]

The observationally relevant perturbations are generated when \(\phi \approx \phi_{\text{COBE}}\). The number of e-foldings between \(\phi_{\text{COBE}}\) and \(\phi_{\text{end}}\), denoted by \(N_{\text{COBE}}\), follows from Eq. (12)
\[
N_{\text{COBE}} \approx \frac{\phi_0^3}{2n(n-1)M_P^2(\phi_0 - \phi_{\text{COBE}})}.
\]

The amplitude of the scalar perturbations, generated during the slow roll phase is given by \(\mathbf{11, 12, 13}\):
\[
\delta_H = \frac{1}{5\pi} \frac{H_{\text{inf}}^2}{\phi} \approx \frac{1}{5\pi} \sqrt{\frac{m_\phi M_P}{2}}\left(\frac{\phi_0^2}{\phi^2}\right) N_{\text{COBE}}^2.
\]

where we have used Eqs. \(\mathbf{9, 10, 11}\).

Again after using these equations, the spectral tilt of the power spectrum and its running are found to be \(\mathbf{11, 12}\)
\[
n_s = 1 + 2\eta - 6\epsilon \approx 1 - \frac{4}{N_{\text{COBE}}},
\]
\[
\frac{dn_s}{d\ln k} = -\frac{4}{N_{\text{COBE}}^2}.
\]

For soft supersymmetry breaking parameters \(m_\phi\) and \(A\) in the range of \(1-10\) TeV, perturbations of the correct size are obtained for \(\phi_0 \sim 10^{14} - 10^{15}\) GeV \(\mathbf{11, 12, 13}\). This results in \(V(\phi) \lesssim 10^{15}\) (GeV)\(^4\). Since reheating in our case happens instantaneously \(\mathbf{12}\), we find \(N_{\text{COBE}} \lesssim 50\). \(\mathbf{13}\)

The expression for the tilt in the power spectrum, see Eq. (10), then implies that \(n_s \approx 0.92\). Although, the tilt is compatible with the current WMAP 3-years data within \(2\sigma\), it is still somewhat towards the lower side.

A very natural question which arises out of this scenario is whether the spectral tilt can at all be improved from 0.92 or not. Note that the tilt in Eq. (10) is a robust prediction of a slow roll inflation near the saddle point, as it does not depend on the detailed form of the potential. Hence any improvement, \(n_s > 0.92\) requires deviations from the saddle point condition Eq. (3).

In the coming section, we argue that it is possible to achieve the spectral tilt \(n_s > 0.92\) within our setup.

### III. Deviation from the Saddle Point

To facilitate the discussion, let us define
\[
\delta = \frac{A^2}{8(n-1)m_\phi^2} \equiv 1 \pm \left(\frac{n-2}{2}\right)^2 \alpha^2,
\]

\(^3\) The importance of \(A\)-term was first highlighted in Ref. \(\mathbf{2}\) in connection to inflation and density perturbations.
where $\alpha \ll 1$. Note that when $\alpha = 0$ and $\delta = 1$ we are back to the saddle point condition \(^4\).

When $\delta > 1$, we will have a point of inflection at $\phi_0$ and two extrema (one maximum, one minimum) near it. The field which is initially trapped in the minimum can tunnel to a point beyond the maximum \(a la\) Coleman-De Luccia, and a period of slow roll inflation with a number of e-foldings $\geq N_{C\text{OB}E}$ with $n_s = 1 - 4/C\text{OB}E$ will follow, provided that $\alpha$ is sufficiently small (for more details see [3]). For larger values of $\alpha$ results deviate from the saddle point calculations, which will only result in $n_s < 0.92$ \(^1_4\). Note however that this is not of interest to us as $n_s$ will lie completely outside the $2\sigma$ limit from the WMAP central value \(^1_2\).

In an opposite case, when $\delta < 1$, there exists only a point of inflection at $\phi_0$ (i.e. $V''(\phi_0) = 0$) where

$$V'(\phi_0) = \left(\frac{n-2}{2}\right)^2 \alpha^2 m_2^2 \phi_0,$$  

(19)

and $V''(\phi_0)$ is given by Eq. [7]. We therefore have

$$V'(\phi) \simeq V'(\phi_0) + \frac{1}{2} V''(\phi_0)(\phi - \phi_0)^2.$$  

(20)

Note that both terms on the right-hand side are positive.

The fact that $V'(\phi_0) \neq 0$ can lead to interesting changes from a saddle point behavior.

Further note that in the previous section, the slow roll inflation was driven by $V''(\phi_0)$. This holds true only if the first term on the right-hand side of Eq. [20] is subdominant for $\phi \leq \phi_{C\text{OB}E}$. After using Eq. [13] this leads to a following bound on parameter $\alpha$ \(^5\)

$$\alpha \lesssim \frac{1}{n(n-1)N_{C\text{OB}E}} \left(\frac{\phi_0}{M_P}\right)^2.$$  

(21)

If this bound is satisfied, the spectral tilt will still be given by Eq. [16] and, therefore $n_s \approx 0.92$ remains valid. In passing we note that there will be no self-reproduction regime unless $\alpha \ll (m_\phi^2 M_P^2)^{1/2}$ \(^3_1_4\), which is a much stronger bound than that in Eq. [21].

However, for a larger value of $\alpha$, we can still have inflation, but $V'(\phi_0)$ affects the slow roll motion of the inflaton during the last $N_{C\text{OB}E}$ number of e-foldings.

The total number of e-foldings during the slow roll of $\phi$ from $\phi_0$ down to $\phi_{eq}$ is given by (from now on $V_0'$ and $V_0''$ stand for $V'(\phi)$ and $V''(\phi)$)

$$N_{tot} \simeq \frac{V(\phi_0)}{M_P^2} \left[ \int_{\phi_{eq}}^{\phi_0} \frac{d\phi}{V_0'} + \int_{\phi_{end}}^{\phi_{eq}} \frac{2d\phi}{V_0''(\phi - \phi_0)^2} \right].$$  

(22)

Note that the two terms in the denominator of the integrand become equal at $\phi_{eq}$, see Eqs. [7][19], where

$$(\phi_0 - \phi_{eq}) = \frac{1}{2} \alpha \phi_0.$$  

(23)

Then we can write

$$N_{tot} \simeq \frac{V(\phi_0)}{M_P^2} \left[ \int_{\phi_{eq}}^{\phi_0} \frac{d\phi}{V_0'} + \int_{\phi_{end}}^{\phi_{eq}} \frac{2d\phi}{V_0''(\phi - \phi_0)^2} \right].$$  

(24)

which, after using Eq. [23], results in \(^6\)

$$N_{tot} \simeq \frac{2}{n(n-1)\alpha} \left(\frac{\phi_0}{M_P}\right)^2.$$  

(25)

It is interesting to note that the two terms on the right-hand side of Eq. [24] gives equal number of e-foldings, i.e. $N_{tot}/2$. The requirement that $N_{tot} \geq N_{C\text{OB}E}$ leads to an upper bound

$$\alpha \lesssim \frac{2}{n(n-1)N_{C\text{OB}E}} \left(\frac{\phi_0}{M_P}\right)^2.$$  

(26)

Therefore, there exists a window where we can have sufficient number of e-foldings, but the saddle point results for the spectral index are not valid any longer. The range of $\alpha$ dictates the trend.

$$\frac{1}{n(n-1)N_{C\text{OB}E}} \left(\frac{\phi_0}{M_P}\right)^2 < \alpha \lesssim \frac{2}{n(n-1)N_{C\text{OB}E}} \left(\frac{\phi_0}{M_P}\right)^2.$$  

(27)

Within this window, $\phi_{C\text{OB}E} > \phi_{eq}$ and, the number of e-foldings follows

$$N_{C\text{OB}E} \simeq \frac{V_0}{M_P^2} \left[ \int_{\phi_{eq}}^{\phi_{C\text{OB}E}} \frac{d\phi}{V_0'} + \int_{\phi_{end}}^{\phi_{eq}} \frac{2d\phi}{V_0''(\phi - \phi_0)^2} \right],$$  

(28)

instead of Eq. [14].

After using Eq. [28], we find

$$(\phi_0 - \phi_{C\text{OB}E}) \simeq \alpha \phi_0 \left[ 1 - \frac{n(n-1)\alpha}{2} \left(\frac{M_P}{\phi_0}\right)^2 N_{C\text{OB}E} \right].$$  

(29)

Eq. [10] then results in (note that $V''(\phi) \approx V''_0(\phi - \phi_0)$)

$$n_s \simeq 1 - 8n(n-1)\alpha \left(\frac{M_P}{\phi_0}\right)^2 \left[ 1 - \frac{n(n-1)\alpha}{2} \left(\frac{M_P}{\phi_0}\right)^2 N_{C\text{OB}E} \right].$$  

(30)

When $\alpha$ saturates the lower bound of the inequality in Eq. [27], we recover our earlier result, $n_s \simeq 1 - 4/N_{C\text{OB}E} \simeq 0.92$.

On the other hand, when the upper bound of the inequality in Eq. [27] is saturated, we find $n_s \simeq 1$. This particular value of $n_s \rightarrow 1$, can be easily understood as, $\phi_{C\text{OB}E} \rightarrow \phi_0$, in which case, $\eta \rightarrow 0$. Therefore the spectral tilt is virtually scale invariant.

\(^4\) A similar analysis is presented in Ref. [3], but for a different purpose.

\(^5\) This is the same as the condition for a successful inflation when $\delta > 1$ \(^3\).

\(^6\) Note that $N_{tot} \rightarrow \infty$ as $\alpha \rightarrow 0$. However Eq. [29] ceases to hold once $\alpha < (m_\phi^2 M_P^2)^{1/2}$, since as mentioned before, we enter the self-reproduction regime. The total number of e-foldings in the slow roll regime is then given by Eq. [13], which coincides with Eq. [22] when $\alpha \sim (m_\phi^2 M_P^2)^{1/2}$. 
Hence within the window we have
\[ 0.92 \leq n_s \leq 1. \] (31)

One comment is in order at this point. As pointed out earlier, for the values of \( \alpha \) given in Eq. (27) there will be no self-reproduction regime in the immediate vicinity of \( \phi_0 \). Therefore we actually have slow roll inflation within the interval \([\phi_e, 2\phi_0 - \phi_e]\), where \( \phi_e \) is given in Eq. (11). Note that \( V'(\phi - \phi_0) \) and \( V''(\phi - \phi_0) \) are even and odd respectively near \( \phi_0 \), see Eqs. (14). This implies that the slope of potential is symmetric around \( \phi_0 \), hence there is the same number of e-foldings in each of the half intervals \([\phi_e, \phi_0]\) and \([2\phi_0 - \phi_e, \phi_0]\).

One can then consider a situation where \( \phi_0 < \phi_{\text{COBE}} \leq 2\phi_0 - \phi_e \). In the extreme case the total number of e-foldings in the interval \([\phi_e, 2\phi_0 - \phi_e]\) is \( N_{\text{COBE}} \sim N_{\text{COBE}}/2 \) in each half interval. This will slightly increase the upper bound on \( \alpha \) obtained in Eq. (27). Note however that \( V''(\phi) > 0 \), thus \( \eta > 0 \), for \( \phi > \phi_0 \). This implies that \( n_s > 1 \) if \( \phi_{\text{COBE}} > \phi_0 \), which is ruled out by the latest WMAP results (12). For this reason we have only considered the case where \( \phi_{\text{COBE}} \leq \phi_0 \), which will result in \( n_s \leq 1 \) (albeit > 0.92).

An important point is to note that the fine-tuning in \( \alpha \) does not get any worse if we require that the spectral tilt be closer to 1. Eq. (21), which implies a bound \( \alpha < 10^{-9} \) in order for the saddle point calculations remain valid (3), see also (14) for the discussion on fine tuning. According to Eq. (27), a larger \( n_s \) is found if \( 10^{-9} < \alpha < 2 \times 10^{-9} \). If any, we have an improvement by a factor of 2 in \( \alpha \).

However, the running of the spectral tilt is slightly different, it depends on \( V' \) and \( V'' \) also. The two limiting regimes for \( \alpha \) gives,
\[ \frac{16}{N_{\text{COBE}}} \leq \frac{d n_s}{d \ln k} \leq \frac{4}{N_{\text{COBE}}}. \] (32)

For a lower limit of \( \alpha \), see Eq. (27), we recover our earlier result, Eq. (17), but for the upper limit, we get a slightly strong running by virtue of \( V'(\phi_0) > V''(\phi_0) \). However for \( N_{\text{COBE}} \sim 50 \), the running of the spectral tilt remains very small, i.e. \( d n_s / d \ln k \sim -0.0064 \).

Finally, let us see what happens to the amplitude of the scalar perturbations within the window in Eq. (27). When the upper bound of the inequality is saturated, we find
\[ \delta_H \simeq \frac{1}{5\pi} \sqrt{\frac{1}{24} n(n-1)(n-2)} \left( \frac{m_\phi M_P}{\phi_0^2} \right)^2 N_{\text{COBE}}: \] (33)

This is smaller by a factor of 4 compared to the saddle point case, see Eq. (15), which is valid when the lower bound of the inequality in Eq. (27) is saturated. Therefore within the allowed window the correct amplitude is obtained with \( m_\phi \) within the TeV scale range.

IV. CONCLUSION

MSSM inflation provides interesting possibility that the spectral tilt can vary in between 0.92 \( \leq n_s \leq 1 \) depending on how flat the potential is in the vicinity of the saddle point. Interestingly, the upper bound on the spectral tilt \( n_s \approx 1 \) is found when the total number of e-foldings is saturated: \( N_{\text{tot}} \approx N_{\text{COBE}} \), while the lower limit \( n_s \approx 0.92 \) depicts the robustness of the saddle point inflation. The running of the spectral tilt remains weak (and well below the observational limits) in both cases. The amplitude of perturbations, as well as the fine-tuning of parameters, remain practically unchanged.

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