Primordial features due to a step in the inflaton potential

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- Based on : D. K. Hazra, M. Aich, R. K. Jain, L. Sriramkumar and T. Souradeep

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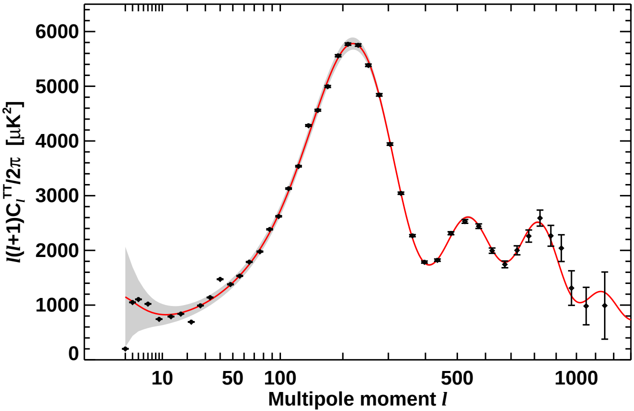
Angular power spectrum from the WMAP 7-year data



The WMAP seven-year data for the CMB TT angular power spectrum (the black dots with error bars) and the theoretical, best fit ΛCDM model with a power law primordial spectrum (the solid red curve). Notice the outliers near the multipoles $\ell = 2$, 22 and 40.

WMAP-7 year data: Points to note

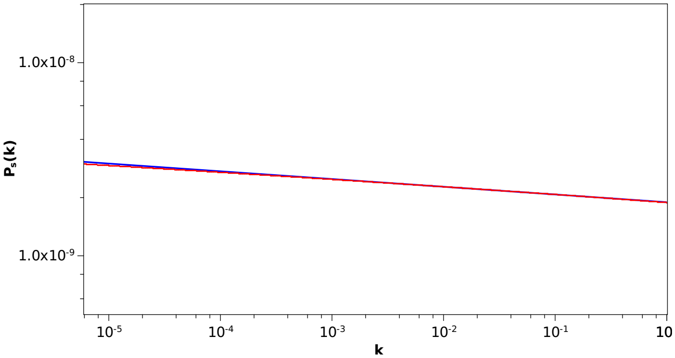
- At the lower multipoles, there exist outliers near $\ell = 2$, 22 and 40
- Statistically, the outliers may be considered to be insignificant
- But, the outliers had appeared in the first year data, and they continue to be present in the seven year data
- So, it is possible that they actually indicate certain non-trivial inflationary dynamics

- The tensor contribution is still undetermined

The scalar power spectrum in slow roll inflation

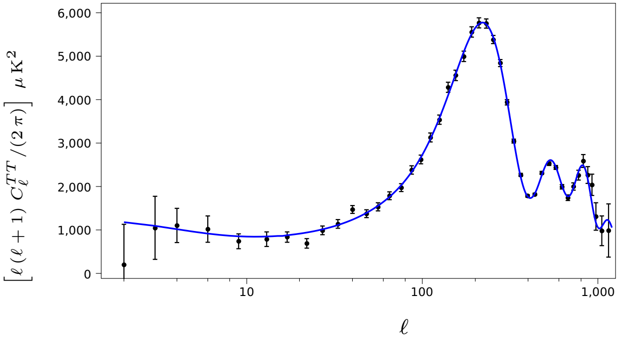
- The power law scalar power spectrum, and the spectrum from the quadratic potential $(m^2\phi^2/2)$ are shown below. They are almost indistinguishable, and they fit the data to the same extent.

Blue $=$ $m^2\phi^2/2$ case
Red $=$ The powerlaw primordial power spectrum



Angular power spectrum in slow roll inflation

- Standard slow roll inflation produces almost the same angular power spectrum as a power law primordial spectrum
- We have plotted below the CMB angular power spectrum for the best fit values of the canonical scalar field described by the quadratic potential.



Fitting the outliers

- Certain oscillatory features in the primordial scalar power spectrum are known to provide a better fit to the data
- For example, punctuated inflation[1] is known to lead to a better fit to the outliers near $\ell = 2$ and $\ell = 22$ than the standard power law spectrum
- The oscillatory features can also be generated with the introduction of a step[2] in a potential that allows a sufficiently long period of slowly rolling inflation

$$\boxed{\tilde{V}(\phi) = V(\phi) \times \left[1 + \alpha \tanh\left(\frac{\phi - \phi_0}{\Delta\phi}\right)\right]}$$

[1] R. K. Jain, P. Chingangbam, J.-O. Gong, L. Sriramkumar and T. Souradeep, JCAP **0901**, 009 (2009)

[2] J. A. Adams, B. Cresswell, R. Easther, Phys. Rev. D **64**, 123514 (2001); L. Covi, J. Hamann, A. Melchiorri, A. Slosar and I. Sorbera, Phys. Rev. D **74**, 083509 (2006); M. J. Mortonson, C. Dvorkin, H. V. Peiris and W. Hu, Phys. Rev. D **79**, 103519 (2009).

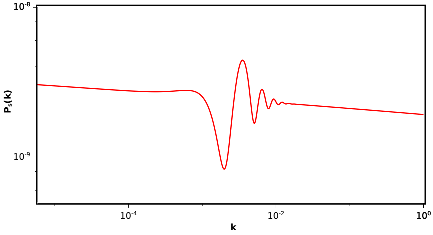
The slow roll parameters

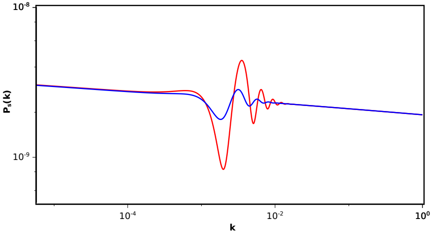
- The following two parameters characterize slow roll inflation

$$\boxed{\epsilon = -\frac{\dot{H}}{H^2}, \eta = -\frac{\ddot{\phi}}{H\dot{\phi}}}$$

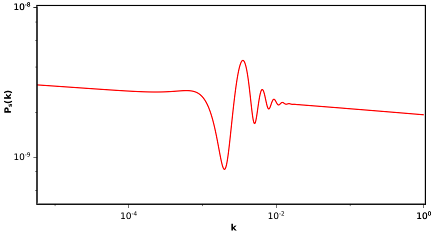
  If the inflaton is rolling slowly down a potential, then $(\epsilon,\ \eta) << 1$
- When we introduce a step in the potential, the field experiences a fast roll near the location of the step (ϕ_0)
- The parameter α determines the strength of the step and $\Delta\phi$ characterizes its width
- These parameters can be used to can tune the location, the strength and the duration of the fast roll period

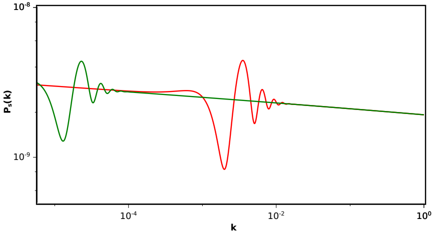
Effects of α



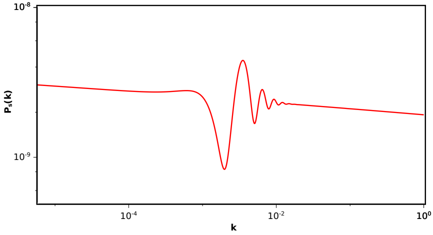


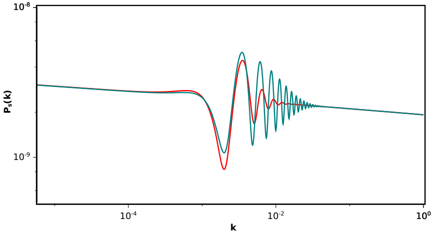
Effects of ϕ_0





Effects of $\Delta\phi$





Which of these oscillations are favored by the CMB data?

- In the case of quadratic potential, it is known that introduction of the step improves the fit to the outliers near $\ell = 22$ and 40
- For example, it is found that $\chi^2_{\rm eff}$ reduces by 7-8 when compared with a featureless, power law scalar spectrum

Aims of the work

The aims of our work are twofold:

- Firstly, we wish to examine whether, with the introduction of a step, other inflationary models too perform equally well against the CMB data, as the quadratic potential does.
- Secondly, the quadratic potential leads to a reasonable amount of tensors, and such a model will be ruled out if tensors are not detected corresponding to a tensor-to-scalar ratio of, say, $r \simeq 0.1$. So, we would also like to consider models that leads to a tensor-to-scalar ratio of $r < 0.1$, so that suitable alternative models exist if the tensors turn out to be small.

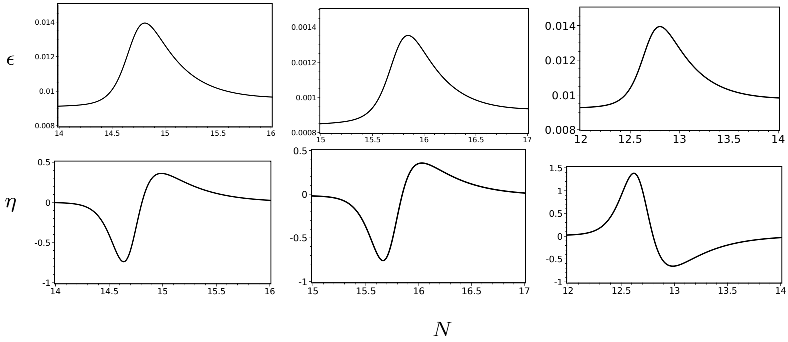
- We have evaluated the tensor contribution exactly for all the models, and have included it in our analysis

The inflationary models we have considered

- 1. Canonical scalars: Here we have considered the quadratic model
  $V(\phi) = (m^2\,\phi^2/2)$
  and the small field model
  $V(\phi) = V_0\,\left[1 - (\phi/\mu)^p\right]$
  2. Tachyon models[3]: In this case, the potentials we have considered are
  $V(\phi) = \left(\frac{\lambda}{\cosh\,(\phi/\phi_*)}\right)$
  and
  $V(\phi) = \left(\frac{\lambda}{1+(\phi/\phi_*)^4}\right)$
- All of them lead to slow roll
- We have introduced the step in each of these models and have compared them with the data.

[3] D. A. Steer and F. Vernizzi, Phys. Rev. D **70**, 043527 (2004).

Behavior of ϵ and η during fast roll



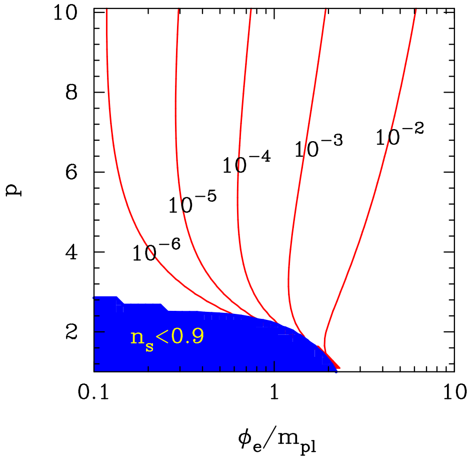
Quadratic model Small field model Tachyon model

The behavior of the first two slow roll parameters for a few different models as the field crosses the step

The tensor contribution

- As we mentioned, the quadratic model leads to a tensor-to-scalar ratio $r \simeq 0.1$
- The tachyon models too lead to a tensor-to-scalar ratio of $r \simeq 0.1$
- As we had pointed out, such models will be ruled out, if the tensors remain undetected at a level corresponding to a tensor-to-scalar ratio of, say, $r \simeq 0.1$
- Keeping this in mind, we have studied a small field model in our analysis where by choosing a specific μ and p we have restricted ourselves to a lower tensor-to-scalar ratio of $r \simeq 0.01$

The tensor amplitude in small field models[4]

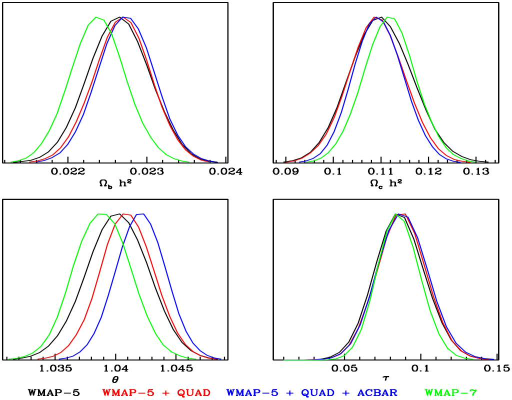


[4] G. Efstathiou and S. Chongchitnan, Prog. Theor. Phys. Suppl. **163**, 204 (2006).

Methodology and datasets

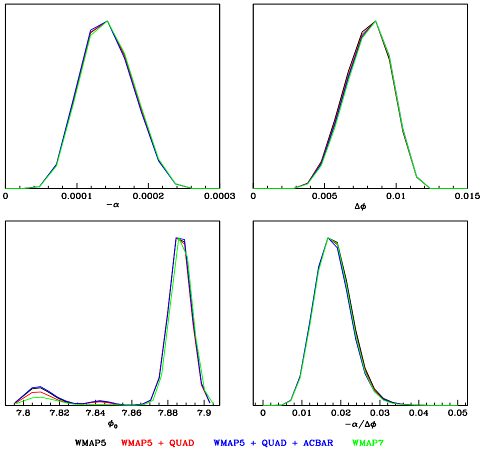
- For our analysis, we have made use of the following datasets:
  1. WMAP-5
  2. WMAP-5 + QUaD-2009
  3. WMAP-5 + QUaD-2009 + ACBAR-2008
  4. WMAP-7
- We have calculated the scalar and tensor power spectra for all the models numerically with high accuracy.
- We have used publicly available CAMB and CosmoMC to compare our models with the data.
- We should mention that we have taken gravitational lensing and the SZ effect into account.

One dimensional likelihoods for the background parameters



The one dimensional likelihood for the background parameters for the case of the small field model with the step.

One dimensional likelihood for α, ϕ_0 and $\Delta\phi$



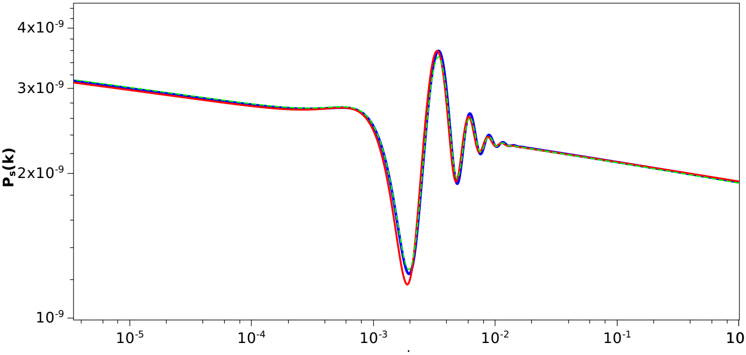
The one dimensional likelihood for the potential parameters for the case of the small field model with the step.

The χ^2_{eff} for the different models and datasets

Datasets / Models	WMAP-5	WMAP-5 + QUaD	WMAP-5 + QUaD + ACBAR	WMAP-7
PL $(4,4)$	2658.40	2757.34	2779.12	7474.48
QP $(1,1)$	$2658.22\ (-0.18)$	$2757.54\ (+0.20)$	$2779.02\ (-0.10)$	$7474.78\ (+0.30)$
QP + step $(4,4)$	$2651.00\ (-7.40)$	$2750.38\ (-6.96)$	$2771.72\ (-7.40)$	$7466.28\ (-8.20)$
SFM $(3,1)$	$2658.26\ (-0.14)$	$2757.46\ (+0.12)$	$2779.06\ (-0.06)$	$7474.78\ (+0.30)$
SFM + step $(6,4)$	$2650.96\ (-7.44)$	$2750.26\ (-7.08)$	$2771.92\ (-7.20)$	$7466.00\ (-8.48)$
TM $(2,1)$	$2658.26\ (-0.14)$	$2757.60\ (+0.26)$	$2779.10\ (-0.02)$	$7474.56\ (+0.08)$
TM + step $(5,4)$	$2651.14\ (-7.26)$	$2750.50\ (-6.84)$	$2772.06\ (-7.06)$	$7465.92\ (-8.56)$

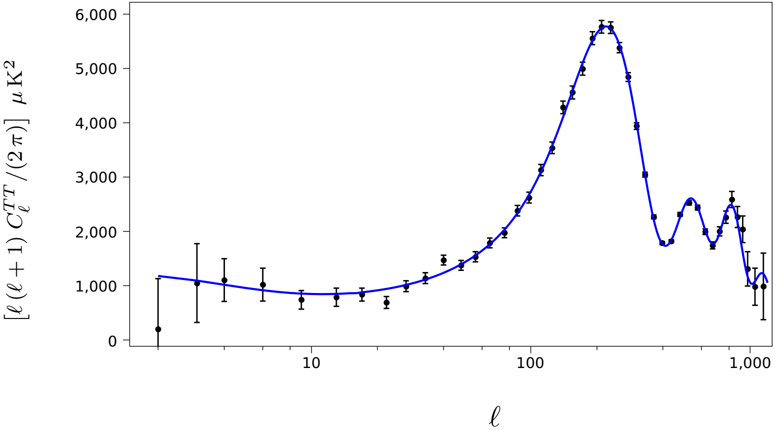
With the introduction of the step, χ^2_{eff} improves by 7-9 in all the cases. Note that the improvement is better for the WMAP-7 data than the WMAP-5 data.

Best fit primordial power spectra for all the models



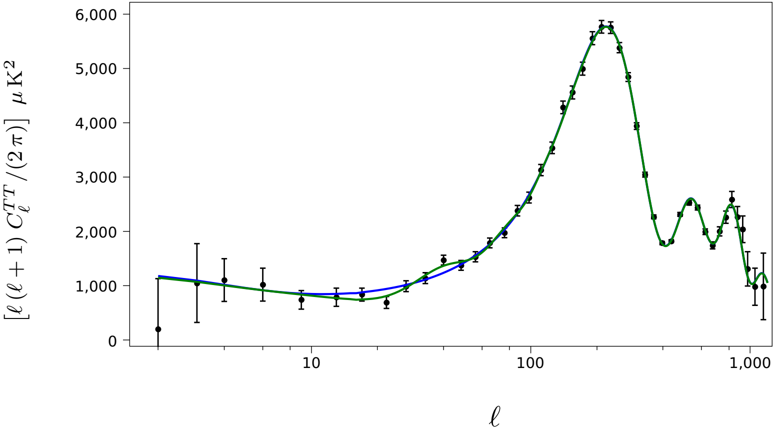
Quadratic model+step   Small field model+step   Tachyon model+step

The C_ℓ^{TT} for the best fit featureless power spectrum



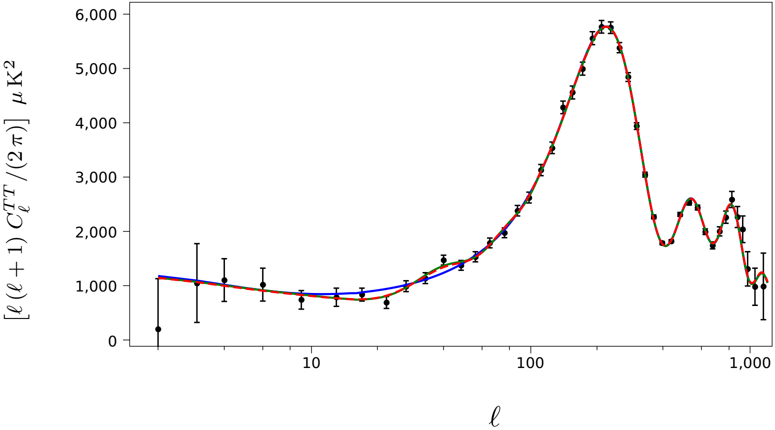
The quadratic model without step

The C_ℓ^{TT} for the best fit power spectrum with features



The quadratic model without step, quadratic model + step

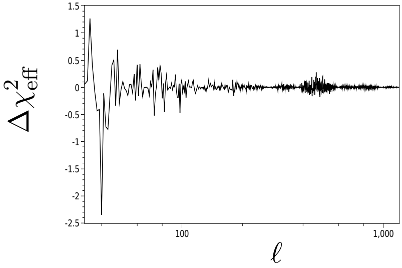
The C_ℓ^{TT} for the best fit power spectrum with features



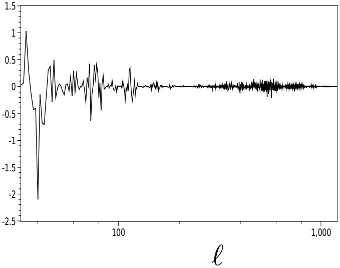
The quadratic model without step, quadratic model + step, small field model + step

Improvement in fit as a function of ℓ (WMAP-7)

- With the introduction of the step, we find that that most of the improvement in $\chi^2_{\rm eff}$ (by about 5-7) occurs over $\ell < 32$.
- For $\ell > 32$, the χ^2_{eff} improvement changes with ℓ as follows for the quadratic and the small field models.



Quadratic model



Small field model

Summary

- Along with the quadratic model we have studied the effect of the step in a small field model and a tachyon model
- In addition to the scalar power spectrum, we have evaluated the tensor power spectrum too exactly, and have included it in our analysis
- The step introduces a burst of oscillations and thus leaves its imprints on the CMB angular power spectrum
- Most of the improvement in the fit come from $\ell < 32$ and the rest comes from $\ell \simeq 40$ (from the C_ℓ^{TT} spectrum only). The improvement of the χ^2 is very small from the C_ℓ^{TE} spectrum
- Comparison with other datasets indicate that introduction of the step doesn't improve fits at higher ℓ 's (at least not as good as low ℓ)
- If ongoing (such as PLANCK and ACT) and/or future observations indicate that the amplitude of the tensor perturbations are rather small, then the quadratic potential and the tachyonic potentials will be ruled out, while a suitable small field model with a step will perform well against the data.