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Introduction of astrophysical reionization models in the Boltzmann code CAMB

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SUMMARY – Various models of the universe ionization history after the standard recombination era have been considered to take into account additional sources of photon and energy production, possibly associated to the early stages of structure and star formation, able to significantly increase the free electron fraction above the residual fraction characterizing the quiescent phase following the recombination epoch. To first approximation, the beginning of the reionization process is identified by the Thomson optical depth, τ. While this simple "τ-parametrization" of the reionization process represents a sufficiently accurate modeling for the interpretation of current CMB data, a great attention has been recently posed on the accurate computation of the reionization signatures in the CMB for a large variety of astrophysical scenarios and physical processes also in the view of WMAP accumulating data and of forthcoming and future experiments beyond WMAP. In this report we describe a modified version of CAMB, the cosmological Boltzmann code for computing the angular power spectrum (APS) of the anisotropies of the cosmic microwave background (CMB), in order to introduce the hydrogen and helium ionization fractions with two astrophysical reionization models, i.e. the suppression and the filtering model, alternative to the original implementation of reionization in the CAMB code. As a significant step forward with respect to previous analyses, the emphasis is posed here to the extension to a first detailed characterization of the polarization BB mode APS. We compare the results obtained for the two considered models and the corresponding simple τ-parametrizations for all the non-vanishing (in the assumed scenarios) modes of the CMB APS.

1 Introduction

Various models of the universe ionization history after the standard recombination era at $z_{\rm rec} \simeq 10^3$ have been considered to take into account additional sources of photon and energy production, possibly associated to the early stages of structure and star formation, able to significantly increase the free electron fraction, χ_e, above the residual fraction ($\sim 10^{-3} - 10^{-4}$) characterizing the quiescent phase following the recombination epoch. These photon and energy production processes associated to this reionization phase may leave imprints in the cosmic microwave background (CMB) providing a crucial "integrated" information on the so-called *dark* and *dawn ages*, i.e. the epochs before or at the beginning of the formation of first cosmological structures. For this reason, among the extraordinary results achieved by the *Wilkinson Microwave Anisotropy Probe* (WMAP) mission, the contribution to the understanding of the cosmological reionization process has received a great attention.

To first approximation, the beginning of the reionization process is identified by the Thomson optical depth, τ. According to the seven-year WMAP analysis [10], the current uncertainty on τ is $= \pm 0.015$, almost independently on the specific model considered. Under various hypotheses (simple ΛCDM model with six parameters, inclusion of curvature and dark energy, of different kinds of isocurvature modes, of neutrino properties, of primordial helium mass fraction, or of a reionization width) the best fit of τ lies in the range 0.086–0.089. On the other hand, allowing for the presence of primordial tensor perturbations or (and) of a running in the power spectrum of primordial perturbations the best fit of τ goes to 0.091–0.092 (0.096).

While this simple "τ-parametrization" of the reionization process and, in particular, of its imprints on the CMB anisotropy likely represents a sufficiently accurate modeling for the interpretation of current CMB data, a great attention has been recently posed on the accurate computation of the reionization signatures in the CMB for a large variety of astrophysical scenarios and physical processes (see e.g. [11, 5, 3, 4, 6, 9, 7, 12, 16]) also in the view of WMAP accumulating data and of forthcoming and future experiments beyond WMAP (see [1] for a review).

The cosmological reionization leaves imprints on the CMB depending on the (coupled) ionization and thermal history. They can be divided in three categories[1]: *i*) generation of CMB Comptonization and free-free spectral distortions associated to the IGM electron temperature increasase during the reionization epoch, *ii*) suppression of CMB temperature anisotropes at large multipoles, ℓ, due to photon diffusion, and *iii*) increasing of the power of CMB polarization and temperature-polarization cross-correlation anisotropy at various multipole ranges, mainly depending on the reionization epoch, because of the delay of the effective last scattering surface.

In this report we focus on the numerical treatment of the aspects *ii*) and *iii*). We describe a modified version of CAMB, the cosmological Boltzmann code for computing the angular power spectrum (APS) of the anisotropies of the cosmic microwave background (CMB), in order to introduce the hydrogen and helium ionization fractions with two astrophysical reionization models, i.e. the suppression and the filtering model [14, 2], alternative to the original implementation of reionization in the CAMB code. Of course, the methods described here can be directly applied to any other astrophysical reionization model, while only for very different physical scenarios (e.g. exotic processes with dramatically different evolutionary behavior possibly occurring at much more higher redshifts) a specific care in some pieces of algorithms of the code may be needed (this aspect will be the subject of a future work). As

[1] Inhomogeneous reionization also produces CMB secondary anisotropies that dominate over the primary CMB component for $\ell \gtrsim 4000$ and can be detected by upcoming experiments, like the Atacama Cosmology Telescope or ALMA [13, 8].

a significant step forward with respect to previous analyses [2], the emphasis is posed here to the extension to a first detailed characterization of the polarization BB mode APS.

By implementing the source file $reionization.f90$, that defines the *Reionization module*, we are able to parametrize the desired reionization history and to supply the corresponding ionization fraction as function of redshift [14, 2, 15].

2 Subroutine modifications in Reionization module

In this section we give a brief description of the implemented routines, comparing them with the standard ones and analyzing the differences between each other.

The first variation concern the *type ReionizationParams*, where we included a new logical variable, *history*, read from the *params.ini* file, by which the user can discriminate between the models. When its value is set to *true* the suppression model, also known as $CF06$, is taken into account, otherwise is reproduced the filtering model parametrization, $G00$.

The main function of the original module, *Reionization_xe*, has been now divided in two parts, $Reionization\_xeCF$ and $Reionization\_xeG$. Both of them calculates the best fit of the ionization fraction for each given redshift value, by means of different fitting functions (see [15]).

With this approach is not necessary to parametrize χ_e in terms of the variable *WindowVarMid*:

$$y = (1+z)^{3/2}\,, \tag{1}$$

where the value of the exponent is given within the constant *Rionization_zexp*. Initial parameter values have been revisited, such as the maximum redshift at which χ_e varies, fixed to 30 instead of 40, the corresponding scale factor, *astart*, related to z by

$$a = \frac{1}{1+z}\,. \tag{2}$$

Therefore, the original relation

$$astart = \frac{1}{1 + redshift + 8delta\_redshift} \tag{3}$$

is changed to

$$astart = \frac{1}{1 + redshift + 14delta\_redshift} \tag{4}$$

in order to leave unchanged the CAMB standard values.

In the function *Reionization_timesteps* the minimum number of time steps between *tau_start* and *tau_complete*, the relevant times for the reionization process, has been incremented to 1000, while the functions:

- $Reionization\_doptdepth(z)$, the subroutine that expresses the integral optical depth in terms of the scale factor,
- $Reionization\_GetOptDepth(Reion, ReionHist)$, the routine which evaluates the integral of the optical depth in the redshift interval $(0, z^{reion}_{max})$,

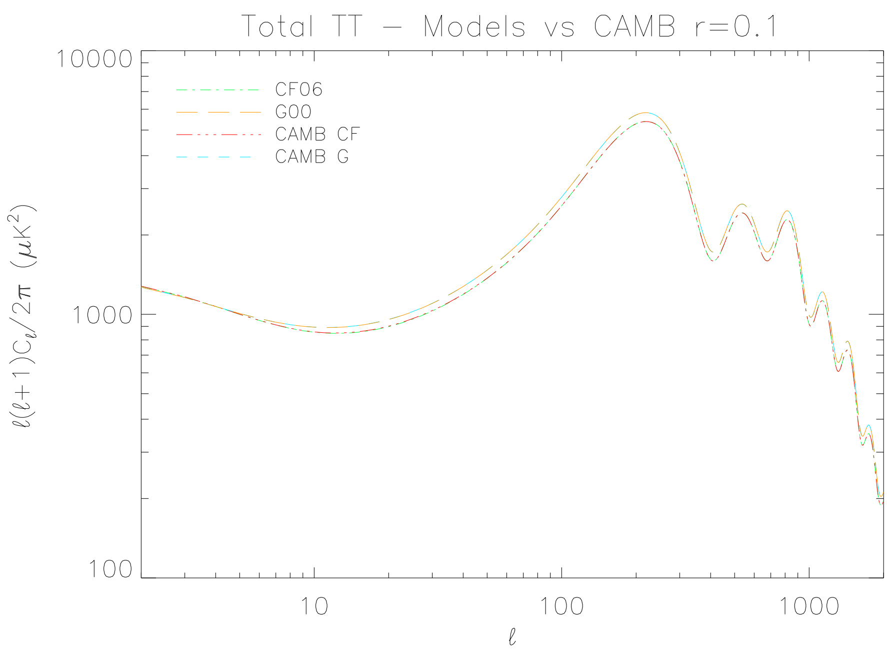

Figure 1: TT APS: comparison between the models and CAMB.

- *Reionization_zreFromOptDepth*(*Reion*, *ReionHist*), a general routine to find the z_{re} parameter given optical depth,
- *Reionization_SetFromOptDepth*(*Reion*, *ReionHist*), the subroutine that calculates the redshift of reionization,

are no longer necessary for the implementation of the adopted ionization histories. In fact, the optical depth, given by

$$\tau = \int_0^{\eta_0} d\eta a n_e \sigma_T \, , \tag{5}$$

being n_e the free electron density, σ_T the Thomson cross section and η the conformal time, is given here by the history itself, so it is not computed in the module.

Finally, since in the two astrophysical models the reionization of the helium is included, the total reionization fraction, according to the CAMB notation, is

$$f = 1 + f_{He} \, . \tag{6}$$

It gives $f_{CF06} = 1.12721$ for the suppression model and $f_{G00} = 1.12480$ for the filtering model [14, 2].

3 Subroutine modifications in ThermoData module

The *Thermodata* module, implemented in *modules.f90* source file, contains the subroutine *inithermo(taumin, taumax)*, which evaluates the unperturbed baryon temperature and ionization fraction as function of time. If there is reionization, the function discriminates between the models, smoothly increases χ_e to the requested value and sets the *actual_opt_depth* to the value imposed by the corresponding model.

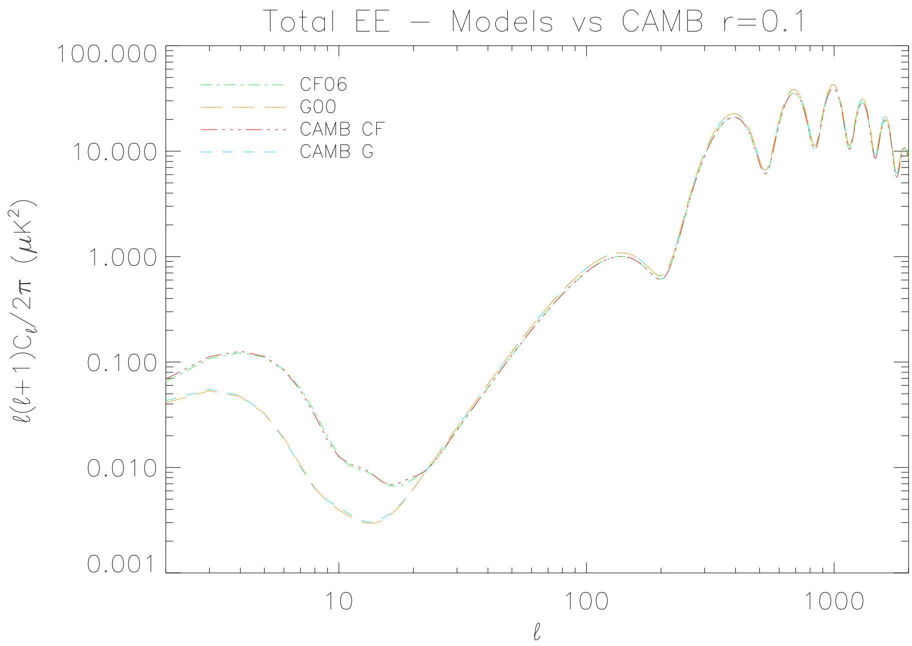

Figure 2: EE APS: comparison between the models and CAMB.

4 Comparison between models

Figs. 1, 2, 3 and 4 show respectively the temperature (TT), polarization (EE, BB), and cross-correlation (TE) modes of the APS obtained from the two adopted astrophysical reionization histories (denoted as "models" in the captions) and compare them to the results of the original version of CAMB (denoted as "CAMB" in the captions), setting the same cosmological parameters and the corresponding optical depth (note that in Fig. 4 we display the module of the cross-correlation APS). In addition, the lensing was taken into account and the various C_ℓ plotted represent the total ones, given by the sum of scalar and tensor contributions. A tensor to scalar ratio of primordial perturbation $r = 0.1$ is assumed here for numerical estimates.

Figs. 5, 6, 7 and 8 plot respectively the relative differences between the models and CAMB, according to the relation:

$$RelDiff = \frac{C_{\ell,mod} - C_{\ell,CAMB}}{0.5(C_{\ell,mod} + C_{\ell,CAMB})} \tag{7}$$

(note that in Fig. 8 we display the module of the difference of the cross-correlation APS).

Differences among the suppression model and the original CAMB, run with the same cosmological parameters as imposed by the corresponding model, are greater than in the case of the filtering model, especially in the EE and TE components of the APS. The difference is more appreciable at low multipoles, in particular at $\ell <$ few tens, i.e. at the large and intermediate angular scales, where the differences between these two models grows up, as expected for relatively late reionization processes.

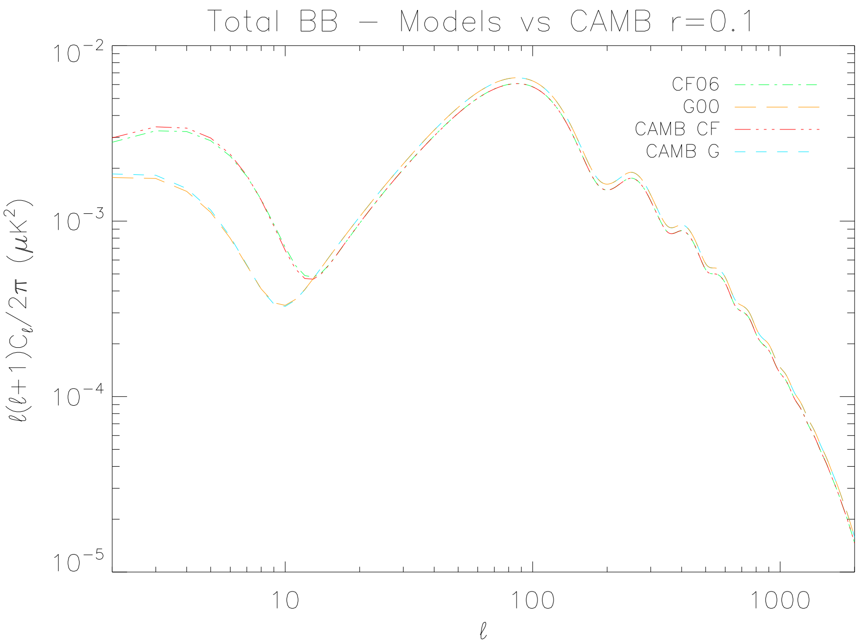

Figure 3: BB APS: comparison between the models and CAMB.

5 Conclusion

In this report we described a modified version of CAMB, the cosmological Boltzmann code for computing the angular power spectrum (APS) of the anisotropies of the cosmic microwave background (CMB), in order to introduce the hydrogen and helium ionization fractions with two astrophysical reionization models, i.e. the suppression and the filtering model, alternative to the original implementation of reionization in the CAMB code beyond his simple τ-parametrization. As a significant step forward with respect to previous analyses, the emphasis has been posed here to the extension to a first detailed characterization of the polarization BB mode APS. We compared the results obtained for the two considered models and the corresponding simple τ-parametrizations for all the non-vanishing (in the assumed scenarios) modes of the CMB APS. Differences among the suppression model and the original CAMB, run with the same cosmological parameters as imposed by the corresponding model, are greater than in the case of the filtering model, especially in the EE and TE components of the APS. The difference is more appreciable at low multipoles, in particular at $\ell <$ few tens, i.e. at the large and intermediate angular scales.

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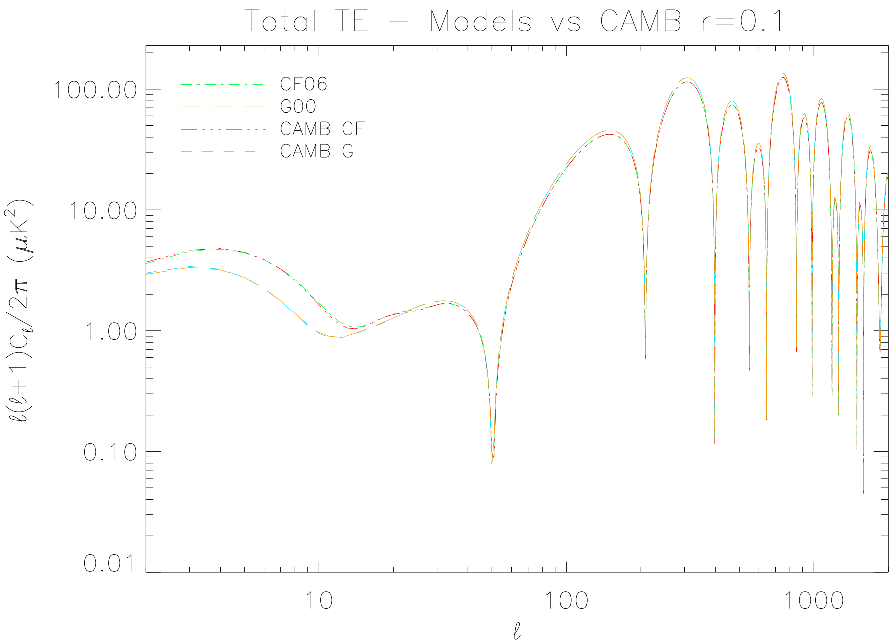

Figure 4: TE APS: comparison between the models and CAMB.

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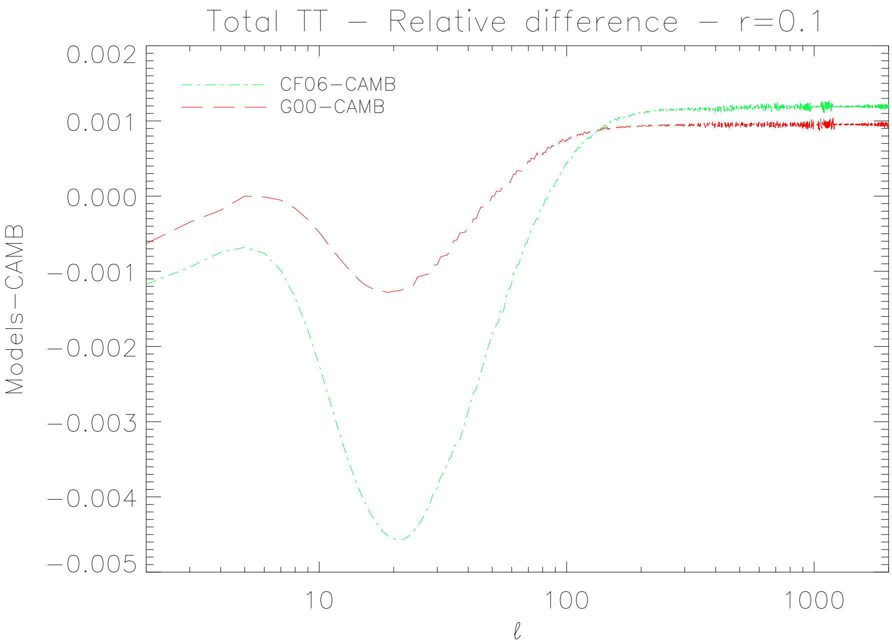

Figure 5: TT APS: relative differences between the models and CAMB.

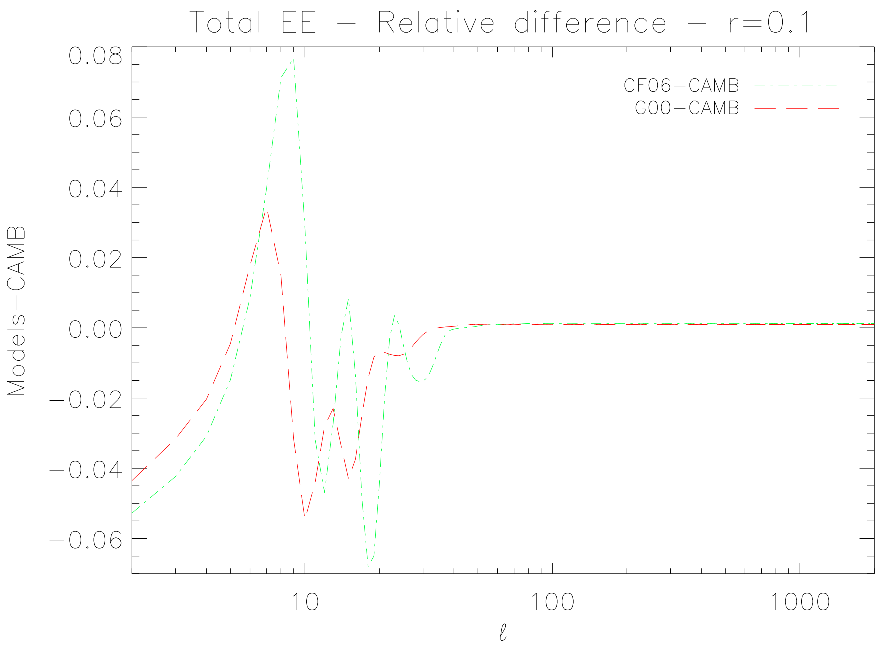

Figure 6: EE APS: relative differences between the models and CAMB.

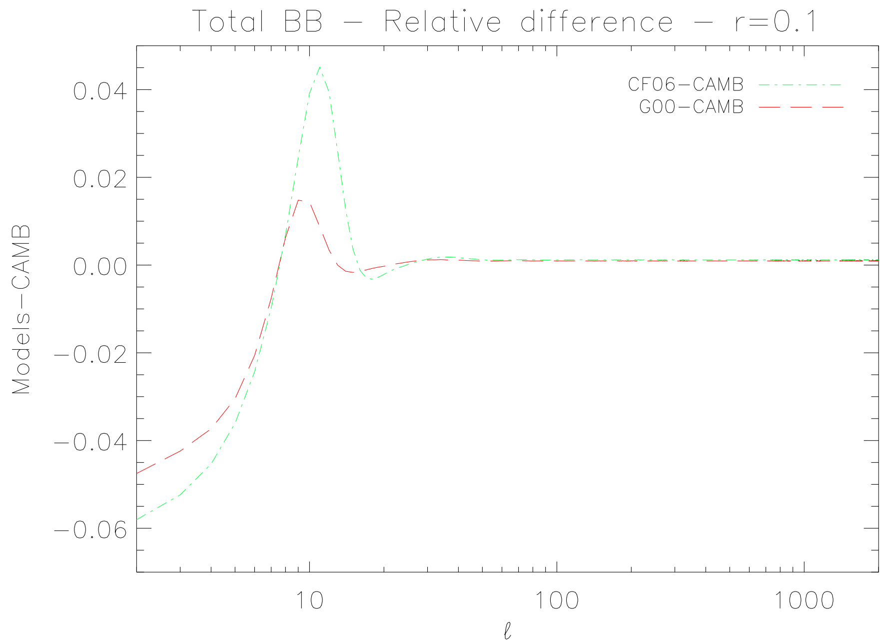

Figure 7: BB APS: relative differences between the models and CAMB.

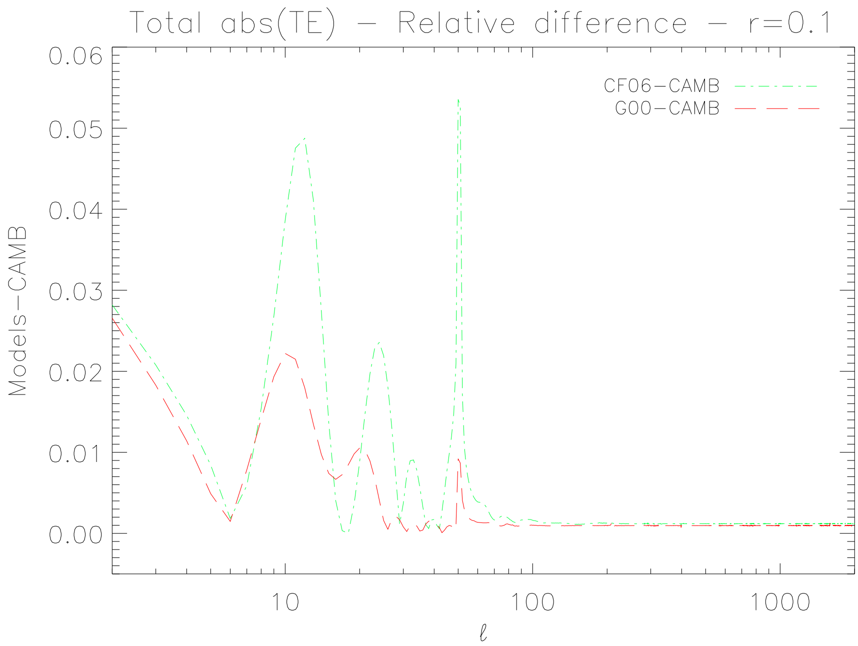

Figure 8: TE APS: relative differences between the models and CAMB.