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Cosmological constraints from Archeops


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Abstract. We analyze the cosmological constraints that Archeops (Benoït et al. 2003) places on adiabatic cold dark matter models with passive power-law initial fluctuations. Because its angular power spectrum has small bins in position at multipole $l_{\text{peak}} = 220 \pm 6$, height and width. An analysis of Archeops data in combination with other CMB datasets constrains the baryon content of the Universe, $\Omega_b h^2 = 0.025_{-0.003}^{+0.003}$, compatible with Big–Bang nucleosynthesis and with a similar accuracy. Using cosmological priors obtained from recent non–CMB data leads to tighter constraints on the total density, e.g. $\Omega_m h = 1.00_{-0.02}^{+0.01}$ using the HST determination of the Hubble constant. An excellent absolute calibration consistency is found between Archeops and other CMB experiments, as well as with the previously quoted best fit model. The spectral index $n$ is measured to be $1.04_{-0.12}^{+0.10}$ when the optical depth to reionization, $\tau$, is allowed to vary as a free parameter, and $0.96_{-0.04}^{+0.03}$ when $\tau$ is fixed to zero, both in good agreement with inflation.

Key words. cosmic microwave background – cosmological parameters – early Universe – large–scale structure of the Universe

1. Introduction

A determination of the amplitude of the fluctuations of the cosmic microwave background (CMB) is one of the most
promising techniques to overcome a long standing problem in cosmology – setting constraints on the values of the cosmological parameters. Early detection of a peak in the region of the so-called first acoustic peak ($\ell \approx 200$) by the Saskatoon experiment (Netterfield et al. 1997), as well as the availability of fast codes to compute theoretical amplitudes (Seljak et al. 1996) has provided a first constraint on the geometry of the Universe (Lineweaver et al. 1997; Hancock et al. 1998). The spectacular results of Boomerang and Maxima have firmly established the fact that the geometry of the Universe is very close to flat (de Bernardis et al. 2000; Hanany et al. 2000; Lange et al. 2001; Balbi et al. 2000). Tight constraints on most cosmological parameters are anticipated from the Map (Bennett et al. 1997) and Planck (Tauber et al. 2000) satellite experiments. Although experiments have already provided accurate measurements over a wide range of $\ell$, degeneracies prevent a precise determination of some parameters using CMB data alone. For example, the matter content $\Omega_m$ cannot be obtained independently of the Hubble constant. Therefore, combinations with other cosmological measurements (such as supernovae, Hubble constant, and light element fractions) are used to break these degeneracies. Multiple constraints can be obtained on any given parameter by combining CMB data with any of these other measurements. It is also of interest to check the consistency between these multiple constraints. In this letter, we derive constraints on a number of cosmological parameters using the measurement of CMB anisotropy by the Archeops experiment (Benoît et al. 2003). This measurement provides the most accurate determination presently available of the angular power spectrum at angular scales of the first acoustic peak and larger.

2. Archeops angular power spectrum

The first results of the February 2002 flight of Archeops are detailed in Benoît et al. (2003). The band powers used in this analysis are plotted in Fig. 1 together with those of other experiments (CBDMVC for COBE, Boomerang, Dasi, Maxima, VSA, and CBI; Tegmark et al. 1996; Netterfield et al. 2002; Halverson et al. 2002; Lee et al. 2001; Scott et al. 2002; Pearson et al. 2002). Also plotted is a $\Lambda$CDM model (computed using CAMB, 2000), with the following

$$\Omega_m = 0.3, \quad \Omega_{\Lambda} = 0.7, \quad H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}.$$
cosmological parameters: $\Theta = (\Omega_m, \Omega_b h^2, h, n, Q, \tau) = (1.00, 0.7, 0.02, 0.70, 1.00, 18 \mu K, 0.)$ where the parameters are the total energy density, the energy density of a cosmological constant, the baryon density, the normalized Hubble constant ($H_0 = 100 h$ km s$^{-1}$ Mpc$^{-1}$), the spectral index of the scalar primordial fluctuations, the normalization of the power spectrum and the optical depth to reionization, respectively. The predictions of inflationary motivated adiabatic fluctuations, a plateau in the power spectrum at large angular scales followed by a first acoustic peak, are in agreement with the results from Archeops and from the other experiments. Moreover, the data from Archeops alone provides a detailed description of the power spectrum around the first peak. The parameters of the peak can be studied without a cosmological prejudice (Knox et al. 2000; Douspis & Ferreira 2002) by fitting a constant term, here fixed to match COBE amplitude, and a Gaussian function of $\ell$. Following this procedure and using the Archeops and COBE data only, we find (Fig. 2) for the location of the peak $\ell_{\text{peak}} = 220 \pm 6$, for its width $FWHM = 192 \pm 12$, and for its amplitude $\delta T = 71.5 \pm 2.0 \mu K$ (error bars are smaller than the calibration uncertainty from Archeops alone, because COBE amplitude is used for the constant term in the fit). This is the best determination of the parameters of the first peak to date, yet still compatible with other CMB experiments.

### 3. Model grid and likelihood method

To constrain cosmological models we constructed a $4.5 \times 10^6$ $C_\ell$ database. Only inflationary motivated models with adiabatic fluctuations are being used. The ratio of tensor to scalar modes is also set to zero. As the hot dark matter component modifies mostly large $\ell$ values of the power spectrum, this effect is neglected in the following. Table 1 describes the corresponding gridding used for the database. The models including reionization have been computed with an analytical approximation (Griffiths et al. 1999).

<table>
<thead>
<tr>
<th>$\Omega_m$</th>
<th>$\Omega_b$</th>
<th>$\Omega_b h^2$</th>
<th>$h$</th>
<th>$n$</th>
<th>$Q$</th>
<th>$\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min.</td>
<td>0.7</td>
<td>0.0</td>
<td>0.00915</td>
<td>0.25</td>
<td>0.650</td>
<td>11</td>
</tr>
<tr>
<td>Max.</td>
<td>1.40</td>
<td>1.0</td>
<td>0.0347</td>
<td>1.01</td>
<td>1.445</td>
<td>27</td>
</tr>
<tr>
<td>Step</td>
<td>0.05</td>
<td>0.1</td>
<td>0.00366</td>
<td>*1.15</td>
<td>0.015</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Table 1.** The grid of points in the 7 dimensional space of cosmological models that was used to set constraint on the cosmological parameters. 

For $h$ we adopt a logarithmic binning: $h(i+1) = 1.15 \cdot h(i)$; $Q$ is in $\mu K$.

4. **Cosmological parameter constraints**

#### 4.1. Archeops

We first find constraints on the cosmological parameters using the Archeops data alone. The cosmological model that presents the best fit to the data has a $\chi^2_{\text{gen}} = 6.9$. Figure 3 gives confidence intervals on different pairs of parameters. The Archeops data constrain the total mass and energy density of the Universe ($\Omega_{\text{tot}}$) to be greater than 0.90, but it does not provide strong limits on closed Universe models. Figure 3 also shows that $\Omega_{\text{tot}}$ and $h$ are highly correlated (Douspis et al. 2001b). Adding the HST constraint for the Hubble constant, $H_0 = 72 \pm 8$ km s$^{-1}$ Mpc$^{-1}$ (68% CL, Freedman et al. 2001), leads to the tight constraint $\Omega_{\text{tot}} = 0.96^{-0.09}_{+0.04}$ (full line in Fig. 3), indicating that the Universe is flat.

Using Archeops data alone we can set significant constraints neither on the spectral index $n$ nor on the baryon constant $\Omega_b h^2$ because of lack of information on fluctuations at small angular scales.
4.2. COBE, Archeops, CBI

We first combine only COBE/DMR, CBI and Archeops so as to include information over a broad range of angular scales, $2 \leq \ell \leq 1500$, with a minimal number of experiments. The results are shown in Fig. 4, with a best model $\chi^2_{\text{gen}} = 9/20$. The constraint on open models is stronger than previously, with a total density $\Omega_{\text{tot}} = 1.16^{+0.21}_{-0.20}$ at 68% CL and $\Omega_{\text{tot}} > 0.90$ at 95% CL. The inclusion of information about small scale fluctuations provides a constraint on the baryon content, $\Omega_b h^2 = 0.019^{+0.006}_{-0.007}$ in good agreement with the results from BBN (O’Meara et al. 2001: $\Omega_b h^2 = 0.0205 \pm 0.0018$). The spectral index $n = 1.06^{+0.11}_{-0.14}$ is compatible with a scale invariant Harrison–Zel’dovich power spectrum.

1 For CBI data, we used only the joint mosaic band powers and restrict ourselves to $\ell \leq 1500$. 

4.3. Archeops and other CMB experiments

By adding the experiments listed in Fig. 1 we now provide the best current estimate of the cosmological parameters using CMB data only. The constraints are shown in Figs. 5 and 6 (left). The combination of all CMB experiments provides

Fig. 4. Likelihood contours for (COBE + Archeops + CBI) in the $(\Omega_\Lambda, \Omega_{\text{tot}})$, $(H_0, \Omega_{\text{tot}})$, $(\Omega_{\text{tot}}, n)$ and $(\Omega_b h^2, n)$ planes.

Fig. 5. Likelihood contours in the $(\tau, n)$ and $(\tau, \Omega_b h^2)$ planes using Archeops + CBDMVC datasets.

Fig. 6. Likelihood contours in the $(\Omega_{\text{tot}}, \Omega_\Lambda)$ and $(\Omega_{\text{tot}}, \Omega_b h^2)$ planes. Left: constraints using Archeops + CBDMVC datasets. Right: adding HST prior for $H_0$.

Fig. 7. Best model obtained from the Archeops + CBDMVC + HST analysis with recalibrated actual datasets. The fitting allowed the gain of each experiment to vary within their quoted absolute uncertainties. Recalibration factors, in temperature, which are applied in this figure, are 1.00, 0.96, 0.99, 1.00, 0.99, 1.00, 1.01, for COBE, Boomerang, Dasi, Maxima, VSA, CBI and Archeops respectively, well within 1 σ of the quoted absolute uncertainties (<1, 10, 4, 4, 3.5, 5 and 7%).
Table 2. Cosmological parameter constraints from combined datasets. Upper and lower limits are given for 68% CL. See text for details on priors. The central values are given by the mean of the likelihood. The quoted error bars are at times smaller than the parameter grid spacing, and are thus in fact determined by an interpolation of the likelihood function between adjacent grid points.

<table>
<thead>
<tr>
<th>Data</th>
<th>(\Omega_{\text{tot}})</th>
<th>(n_s)</th>
<th>(\Omega_b h^2)</th>
<th>(h)</th>
<th>(\Omega_c)</th>
<th>(\tau)</th>
<th>(\chi^2_{\text{tot}}/\text{d.o.f.})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Archeops</td>
<td>&gt;0.90</td>
<td>1.15+0.30</td>
<td>-0.30</td>
<td>-</td>
<td>&lt;0.03</td>
<td>&lt;0.25</td>
<td>&lt;0.45</td>
</tr>
<tr>
<td>Archeops + COBE + CBI</td>
<td>1.16+0.24+0.28</td>
<td>1.06+0.11</td>
<td>0.019+0.006</td>
<td>0.25</td>
<td>&lt;0.65</td>
<td>&lt;0.05</td>
<td>&lt;0.45</td>
</tr>
<tr>
<td>CMB</td>
<td>1.18+0.22+0.30</td>
<td>1.06+0.10</td>
<td>0.024+0.003</td>
<td>0.25</td>
<td>&lt;0.85</td>
<td>&lt;0.05</td>
<td>&lt;0.45</td>
</tr>
<tr>
<td>Archeops + CMB</td>
<td>1.15+0.12+0.18</td>
<td>1.04+0.10</td>
<td>0.022+0.004</td>
<td>0.25</td>
<td>&lt;0.85</td>
<td>&lt;0.05</td>
<td>&lt;0.45</td>
</tr>
<tr>
<td>Archeops + CMB + (\tau = 0)</td>
<td>1.13+0.12+0.18</td>
<td>0.96+0.10</td>
<td>0.021+0.002</td>
<td>0.25</td>
<td>&lt;0.80</td>
<td>0.00</td>
<td>40/68</td>
</tr>
<tr>
<td>Archeops + CMB + (\Omega_{\text{tot}} = 1)</td>
<td>1.00</td>
<td>1.04+0.10</td>
<td>0.021+0.003</td>
<td>0.25</td>
<td>&lt;0.80</td>
<td>0.00</td>
<td>40/68</td>
</tr>
<tr>
<td>Archeops + CMB + HST</td>
<td>1.00+0.03+0.02</td>
<td>1.04+0.10</td>
<td>0.022+0.003</td>
<td>0.25</td>
<td>&lt;0.80</td>
<td>0.00</td>
<td>40/68</td>
</tr>
<tr>
<td>Archeops + CMB + HST + (\tau = 0)</td>
<td>1.00+0.03+0.02</td>
<td>0.96+0.04</td>
<td>0.021+0.001</td>
<td>0.25</td>
<td>&lt;0.80</td>
<td>0.00</td>
<td>40/68</td>
</tr>
<tr>
<td>Archeops + CMB + SN1a</td>
<td>1.04+0.02+0.04</td>
<td>1.04+0.10</td>
<td>0.022+0.004</td>
<td>0.25</td>
<td>&lt;0.80</td>
<td>0.00</td>
<td>40/68</td>
</tr>
<tr>
<td>Archeops + CMB + BBN</td>
<td>1.12+0.12+0.014</td>
<td>1.04+0.10</td>
<td>0.020+0.002</td>
<td>0.25</td>
<td>&lt;0.80</td>
<td>0.00</td>
<td>40/68</td>
</tr>
<tr>
<td>Archeops + CMB + BF(H)</td>
<td>1.11+0.12+0.014</td>
<td>1.03+0.10</td>
<td>0.022+0.004</td>
<td>0.25</td>
<td>&lt;0.80</td>
<td>0.00</td>
<td>40/68</td>
</tr>
<tr>
<td>Archeops + CMB + BF(L)</td>
<td>1.23+0.18+0.12</td>
<td>1.03+0.07</td>
<td>0.021+0.003</td>
<td>0.25</td>
<td>&lt;0.80</td>
<td>0.00</td>
<td>40/68</td>
</tr>
</tbody>
</table>

\(~10\%~) errors on the total density, the spectral index and the baryon content respectively: \(\Omega_{\text{tot}} = 1.15^{+0.12}_{-0.17}, \ n = 1.04^{+0.10}_{-0.12}\) and \(\Omega_b h^2 = 0.023^{+0.002}_{-0.003}\). These results are in good agreement with recent analyses performed by other teams (Netterfield et al. 2002; Pryke et al. 2002; Rubino-Martin et al. 2002; Sievers et al. 2002; Wang et al. 2002). One can also note that the parameters of the \(\Lambda\)CDM model shown in Fig. 1 are included in the 68\% CL contours of Fig. 6 (right).

As shown in Fig. 5 the spectral index and the optical depth are degenerate. Fixing the latter to its best fit value, \(\tau = 0\), leads to stronger constraints on both \(n\) and \(\Omega_b h^2\). With this constraint, the preferred value of \(n\) becomes slightly lower than 1, \(n = 0.96^{+0.03}_{-0.04}\), and the constraint on \(\Omega_b h^2\) from CMB alone is not only in perfect agreement with BBN determination but also has similar error bars, \(\Omega_b h^2\)\(_{\text{CMB}} = 0.201^{+0.002}_{-0.003}\). It is important to note that many inflationary models (and most of the simplest of them) predict a value for \(n\) that is slightly less than unity (see, e.g., Linde 1990; Lyth & Riotto 1999 for a recent review).

4.4. Adding non–CMB priors

In order to break some degeneracies in the determination of cosmological parameters with CMB data alone, priors coming from other cosmological observations are now added. First we consider priors based on stellar candles like HST determination of the Hubble constant (Freedman et al. 2001) and supernovae determination of \(\Omega_m\) and \(\Lambda\) (Perlmutter et al. 1999). We also consider non stellar cosmological priors like BBN determination of the baryon content, (O’Meara et al. 2001), and baryon fraction determination from X-ray clusters (Roussel et al. 2000; Sadat & Blanchard 2001). For the baryon fraction we use a low value, BF(L), \(f_b = 0.031^{+0.32}_{-0.12} + 0.012\) (±10\%), and a high value, BF(H), \(f_b = 0.048^{+0.32}_{-0.12} + 0.014\) (±10\%) (Douspis et al. 2001b and references therein). The results with the HST prior are shown in Fig. 6 (right). Considering the particular combination Archeops + CBDMVC + HST, the best fit model, within the Table 1 grid, is \((\Omega_{\text{tot}}, \Omega_b h^2, h, n, Q, \tau) = (1.00, 0.7, 0.02, 0.665, 0.945, 19.2\text{K}\\text{K}_\odot)\) with a \(\chi^2_{\text{tot}} = 41/68\). The model is shown in Fig. 7 with the data scaled by their best–fit calibration factors which were simultaneously computed in the likelihood fitting process. The constraints on \(h\) break the degeneracy between the total matter content of the Universe and the amount of dark energy as discussed in Sect. 4.1. The constraints are then tighter as shown in Fig. 6 (right), leading to a value of \(\Omega_A = 0.73^{+0.07}_{-0.07}\) for the dark energy content, in agreement with supernovæ measurements if a flat Universe is assumed. Table 2 also shows that Archeops + CBDMVC cosmological parameter determinations assuming either \(\Omega_{\text{tot}} = 1\) or the HST prior on \(h\) are equivalent at the 68\% CL.

5. Conclusion

Constraints on various cosmological parameters have been derived by using the Archeops data alone and in combination with other measurements. The measured power at low \(\ell\) is in agreement with the COBE data, providing for the first time a direct link between the Sachs–Wolfe plateau and the first acoustic peak. The Archeops data give a high signal-to-noise ratio determination of the parameters of the first acoustic peak and of the power spectrum down to COBE scales \((\ell = 15)\), because of the large sky coverage that greatly reduces the sample variance. The measured spectrum is in good agreement with that predicted by simple inflation models of scale–free adiabatic perturbations. Archeops on its own also sets a constraint on open models, \(\Omega_m > 0.90\) (68\% CL). In combination with CBDMVC experiments, tight constraints are shown on cosmological parameters like the total density, the spectral index and the baryon content, with values of \(\Omega_{\text{tot}} = 1.13^{+0.12}_{-0.15}, n = 0.96^{+0.03}_{-0.04}\) and \(\Omega_b h^2 = 0.201^{+0.002}_{-0.003}\) respectively, all at 68\% CL and assuming \(\tau = 0\). These results lend support to the inflationary paradigm. The addition of non–CMB constraints removes degeneracies between different parameters and allows to achieve a 10\% precision on \(\Omega_b h^2\) and \(\Omega_A\) and better than 5\% precision on \(\Omega_{\text{tot}}\).
and $n$. Flatness of the Universe is confirmed with a high degree of precision: $\Omega_{\text{tot}} = 1.00^{+0.03}_{-0.02}$ (Archeops + CMB + HST).

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http://www-supernova.lbl.gov