Archeops’ results on the Cosmic Microwave Background

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Archeops is a balloon–borne experiment dedicated to the measurement of the temperature anisotropies of the cosmic microwave background (CMB) from large angular scales to about 10 arcminutes. A brief introduction to the CMB is given below, followed by a description of the Archeops experiment. Archeops flew on the 7th of February 2002 in the Arctic night from Kiruna (Sweden) to Russia. The analysis of part of these data is described below with the results on the $C_\ell$ spectrum, showing for the first time a continuous link between the large scales and the first acoustic peak. We end up with constraints on the cosmological parameters. We confirm the flatness of the Universe. And, combining the Archeops data with other CMB experiments data and with the HST measurement of $H_0$, we measure for the first time $\Omega_\Lambda$ independently of SuperNovae based results.

1 Brief introduction on the Cosmic Microwave Background

At the very beginning of the history, the Universe was a very hot soup of particles. As it expanded, it became cooler and less dense.

When the Universe was about 300,000 years old, it was cold enough for the electrons and protons to combine and form hydrogen: this is the time of recombination. At about the same period, the photons decoupled from matter and the Universe became transparent. These photons travelled throughout the ages with almost no interaction with the matter (except for the reionization period) and we can now detect them as the cosmic microwave background or CMB.

At the time of recombination, the Universe had a different structure that the one we know now: matter was spread out very evenly. However they should have been some structure in the early universe to give birth to the galaxies and large scale structures we observe now. And such slight increases in matter density should have left an imprint on the CMB. Therefore when the photons decoupled from matter, they carried with them the information on the matter distribution in the early universe. Mapping the temperature fluctuations of these photons as
they appear to us now is mapping the matter density fluctuations as they were at a very early
time, when the photons last interacted with matter.

1.1 The observable

The goal of CMB experiments is then to measure these temperature anisotropies ($\frac{\delta T}{T}$) over all
the directions ($\theta$) of the sky, building a map (or part of a map) of the Universe. Once we have
obtained this map, we decompose it in terms of spherical harmonics:

$$\frac{\delta T}{T}(\theta, \phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta, \phi)$$  \hspace{1cm} (1)

and we can get the power spectrum $C_\ell$ defined as:

$$C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a_{lm}|^2$$  \hspace{1cm} (2)

which contain all the information on the fluctuations if they are Gaussian. $\ell$ can be seen as the
inverse of the size of the structures on the sky: $\theta = 1^\circ$ correspond to $\ell = 200$.

To extract the parameters which describe the early Universe, we compare the measured $C_\ell$
spectrum and the predictions as it is shown on figure 1 for two varying parameters $\Omega_\Lambda$ and $\Omega_0$.
We can then fit for cosmological parameters such as the matter density, the baryon density, the
age of the Universe... For instance the position of the first acoustic peak is highly related to the
total density $\Omega_{\text{tot}}$.

Figure 1: Angular power spectrum for different sets of cosmological parameters values: here $\Omega_\Lambda$ and $\Omega_0$ are being
varied (from Wayne Hu web site).
1.2 What we have learned so far

The search for anisotropies of the CMB temperature across the sky began with Penzias and Wilson in 1965. They estimated the temperature to be isotropic to within about 10% (Penzias A. and Wilson R.\textsuperscript{[1]}).

In 1976, a flying instrument on a U2 spy plane established a 3mK dipolar temperature variation across the sky, arising from the motion of the Solar System with respect to the rest frame defined by the CMB.

In 1989, NASA launched the Cosmic Background Explorer (COBE) (Mather J. et al\textsuperscript{[2]}), a satellite devoted to the study the microwave and infra-red backgrounds. The Far InfraRed Absolute Spectrometer (FIRAS) determined the CMB temperature to be $2.728\pm0.002$K, and showed that any spectral deviations from a Planck spectrum were less than 0.005%. The CMB is the most precise known black body and could only have arisen from the very hot, dense conditions that existed in the early Universe. COBE refined the dipole measurement showing that the Solar System velocity was $371\pm0.5$km/sec in that frame.

Since then, almost all the measurements on the CMB concentrated on smaller angular scales. Anisotropies have now been observed on small angular scales as it is shown on figure\textsuperscript{2}.

The Boomerang collaboration, which used a balloon experiment with bolometer at 300mK flying over Antarctica, provided a detailed map of the first peak which, besides falling at the 1-degree size predicted by inflation, also determined that the universe was flat.

2 Archeops

2.1 The instrument

The heart of the Archeops instrument is made of spider web bolometers cooled down to 100mK using an open $^3$He-$^4$He dilution cryostat. For each bolometers (21 in total in 4 frequency bands: 143, 217, 353 and 545 GHz), we have individual optics with horns and filters at different temperature stages (0.1, 1.6, and 10K).

Before being measured by the bolometers, the photons from the Big Bang are first collected on a Gregorian off–axis aluminium telescope which provides an angular resolution of about 8 arc-minutes at 143 GHz. The technology is the same as for the Planck-HFI satellite.

The scanning strategy is to make circles on the sky during the arctic night in order to minimise the background from the Sun. The speed rate is of 2 round per minutes at an elevation of 41°.

The goals of Archeops are twofold:

- On the scientific side: Thanks to the large sky coverage allowed by the scanning strategy, the first goal of Archeops was to link the plateau at low $\ell$ measured by COBE to the first acoustic peak measurements of balloon and on-ground experiments (see Fig.\textsuperscript{2}). The second scientific goal is the measurement of the polarisation of the galactic dust at 353GHz which is not described here.

- On the technical side: Archeops is a test-bench for Planck-HFI since we are using the same open cycle dilution to cool down the bolometers to 100mK, the same cold optics and the same spider web bolometers. Planck’s launch is planned for February 2007.

2.2 Results on the power spectrum

The results presented here correspond to 12 hours of data on two bolometers (one at 143 and one at 217 GHz). We are only using for the $C_\ell$ computation the north of the galactic plane. This means analysing 8 millions of data points for each bolometers.
The measured noise is better than what was expected according to the Planck design: of the order of $100 \text{mK}/\sqrt{\text{Hz}}$ for the two bolometers used in the analysis presented here.

The Archeops $C_\ell$ spectrum is shown in red on Fig. 2 in 16 bins ranging from $\ell = 15$ to $\ell = 350$. We also show in comparison a selection of other recent experiments and a best-fit theoretical model.

![Figure 2: Archeops power spectrum in 16 bins along with some other recent experiments. A best model fit (continuous line) is obtained. The fitting allowed the gain of each experiment to vary within their quoted absolute uncertainties. Re-calibration factors, in temperature, which are applied in this figure, are 1.00, 0.96, 0.99, 1.00, 0.99, 1.00, and 1.01, for Cobe, Boomerang, Dasi, Maxima, Vsa, Cbi and Archeops resp., well within 1 $\sigma$ of the quoted absolute uncertainties (< 1, 10, 4, 4, 3.5, 5 and 7%).](image)

In order to study the systematic effects that could affect the results, we have made consistency checks as for example a test of rotation (analysing the signal of one circle and subtracting the one of the previous circle), and a difference test (analysing the time-line of the signal at 143 subtracted by the one at 217 GHz). For those two tests we have checked that the corresponding power spectrum is compatible with 0 for all $\ell$.

In addition we have estimated the effect of the dust contamination (mainly present at low $\ell$) and the bolometer time constant and beam uncertainties (resp. at high $\ell$). The have been found to be negligible with respect to statistical error bars. The sample variance at low $\ell$ and the photon noise at high $\ell$ are the major contributors to the final Archeops error bars of Fig. 2.

As one can see on Fig. 2 the main goal of Archeops (ie to provide an accurate link between the large angular scales from Cobe and the first acoustic peak as measured by degree–scale experiments like Boomerang (de Benardis et al [6], Netterfield et al [7]), Cbi (Sievers et al [5]), Dasi (Pryke et al [9]), Maxima (Hanany et al [8], Netterfield et al [1]), Vsa (Rubiño-Martin [10]) has been achieved. In addition we provide the best measurement of the first peak before WMAP with a resolution of $\ell_{\text{peak}} = 220 \pm 6$.

We have compared the map with the ones of Maxima (Hanany et al [8], Lee et al [11]) and the ones of WMAP (Bennet et al [5]), showing that the same fluctuations are observed on all these
maps with a high correlation factor.

2.3 *The cosmological parameters*

Using a large grid of cosmological adiabatic inflationary models described by 7 parameters, one can compute their likelihood with respect to the datasets. An analysis of Archeops data only leads to put constraints on the total mass and energy density of the Universe ($\Omega_{\text{tot}}$) to be greater than 0.9. Adding the constraint of the measurement of $H_0$ by the HST (Freedman et al.\cite{12}) we end up with the measurement $\Omega_{\text{tot}} = 0.96^{+0.09}_{-0.04}$.

In combination with other CMB datasets (COBE, Dasi, Maxima, VSA, CBI) the Archeops data constrain $\Omega_{\text{tot}} = 1.15^{+0.12}_{-0.17}$ and the spectral index $n = 1.04^{+0.10}_{-0.12}$. In addition the baryon content of the Universe is measured to $\Omega_b h^2 = 0.022^{+0.003}_{-0.004}$ which is compatible with the Big-Bang nucleosynthesis (O’Meara et al.\cite{11}) and with a similar accuracy.

Using the recent HST determination of the Hubble constant (Freedman et al.\cite{12}) leads to tight constraints on the total density, e.g. $\Omega_{\text{tot}} = 1.06^{+0.03}_{-0.02}$, i.e. the Universe is flat, and permits to measure $\Omega_\Lambda$ in an independent but compatible way with Supernovae analysis: $\Omega_\Lambda = 0.73^{+0.09}_{-0.07}$.

The constraints are shown in the $(\Omega_{\text{tot}}, \Omega_\Lambda)$ and $(\Omega_{\text{tot}}, \Omega_b h^2)$ planes on figure 3 without (on the left) and with (on the right) the HST prior on the $H_0$ measurement.
3 Summary

For the first time we were able to fill the gap between the large scales measured by COBE and the first acoustic peak.

Combining Archeops measurements with all the CMB experiments (before WMAP) we confirm that the Universe is flat and combined with the $H_0$ measurement done by the HST, we re-measure $\Omega_\Lambda$ independently of the SN based results.

For Planck-HFI: the bolometer noise is better than the Planck design, and the open cycle dilution worked perfectly.

The analysis is in progress to measure galactic dust emission polarisation with the Archeops last flight data. The use of all available bolometers and of a larger sky fraction should yield an even more accurate and broader CMB power spectrum in the near future. The large experience gained on this balloon–borne experiment is providing a large feedback to the Planck – HFI data processing community.

For more details, two articles are available on Archeops: Benoît et al.[13], and Benoît et al,[14].

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