RESULTS ON CMB ANISOTROPIES WITH THE ARCHEOPS BALLOON EXPERIMENT

F.–X. DÉSERT

Laboratoire d'Astrophysique, Observatoire de Grenoble
BP 53, 414 rue de la piscine,
F – 38041 Grenoble Cedex 9 France
E–mail: Francois-Xavier.Desert@obs.ujf-grenoble.fr

AND THE ARCHEOPS COLLABORATION

includes scientists from Caltech (USA), Cardiff Univ., CESR (Toulouse), CSNSM (Orsay), CRTBT (Grenoble), IAS (Orsay), IAP (Paris), IROE (Firenze, Italy), ISN (Grenoble), JPL (USA), LAL (Orsay), LAOG (Grenoble), Landau Institute (Russia), La Sapienza Univ. (Roma, Italy), LAOMP (Toulouse), Maynooth Univ. (Ireland), Minnesota Univ. (USA), PCC (Paris), SPP (Saclay)

ARCHEOPS is a balloon–borne instrument dedicated to measuring cosmic microwave background (CMB) temperature anisotropies. It has a high angular resolution (about 10 arcminutes) in order to constrain high ℓ multipoles, as well as a large sky coverage fraction (30%) in the millimetre domain (from 143 to 545 GHz) in order to minimize the cosmic variance. This is achieved with fast 0.1 K bolometers and cold optics with a design very similar to PLANCK – HFI. They view a well-baffled 1.5 m off-axis telescope pointing at 41 degree elevation. The gondola at a float altitude above 35 km spins across the sky at a rate of 2 rpm which, combined with the Earth rotation, makes a well sampled sky map. We report on the first results obtained from the last flight (12.5 dark hours) that happened from Kiruna (Sweden) to Russia in February 2002. The white noise sensitivity for the 8 best bolometers is measured below $200\,\mu\mathrm{K}_{CMB}\,\mathrm{s}^{1/2}$ per bolometer. The CMB power spectrum is obtained for ℓ values ranging from 20 to 350 with an unprecedented sensitivity. It connects, in a single experiment, COBE large angular scales to the first acoustic peak region. Taken all together, the CMB experiments show good consistency. Consequences on the cosmological parameters are also addressed. With priors on the Hubble constant and the optical depth to reionisation τ, inflation motivated cosmologies are reinforced with a total density equal to 1 (*i.e.* a flat Universe) within 3 percent, the spectral index of scalar perturbation n being 0.96 ± 0.03 and the baryonic density is in very good agreement with other independent estimates based on big bang nucleosynthesis.

Introduction

The Cosmic Microwave Background (CMB) gives many clues as to the origin of the Universe. It contains a wealth of diverse information, in contrast with the other 2 so–called pillars of Cosmology. The advent of BLIP (Background limited Performance) detectors (bolometers at 100 to 300 mK) and mostly sidelobe–free HEMT based interferometers have provided CMB maps with increasing accuracy and resolution in the last 10 years. The fluctuations that are now routinely detected in a few hours–days of integration time (*e.g.* de Bernardis[4] et al. 2000, Netterfield[11] et al. 2002, Hanany[8] et al. 2000, Lee[10] et al. 2001, Pryke[15] et al. 2001, Sievers[19] et al. 2002, Rubiño-Martin[16] et al. 2002) provide vivid proof of the seeds that lead to large–scale structure formation. They are best analysed with spherical harmonic angular power spectrum C_ℓ as a function of multipole ℓ familiar to quantum physics. The generation of the power spectrum is now theoretically understood so that cosmological parameters can be deduced accurately. ARCHEOPS [a] is a CMB bolometer–based instrument with PLANCK – HFI [b] technology that fills a niche where previous experiments were unable to provide strong constraints. Namely, ARCHEOPS seek to join the gap in ℓ between the large angular scales as measured by COBE /DMR and degree–scale experiments, typically for ℓ between 10 and 200. For that purpose, a large sky coverage is needed. The solution was to adopt a spinning payload mostly above the atmosphere, scanning the sky in circles with an elevation of around 41 degrees. The Earth's rotation makes the circle span a large area of the sky.

1. Description of the instrument

The instrument (Benoît et al. 2002)[1] was designed by adapting concepts put forward for PLANCK – HFI and using balloon–borne constraints: namely, an open ^{3}He–^{4}He dilution cryostat cooling spiderweb–type bolometers at 100 mK, cold individual optics with horns at the different temperature stages (0.1, 1.6, 10 K) and the telescope. The Gregorian off–axis aluminum telescope, made of an effective 1.5 m aperture primary and a secondary ellipsoid mirror, provides an angular resolution of about 8 arcminutes at 143 GHz. The whole instrument is baffled so as to avoid stray radiation from the Earth and the balloon. The scan strategy imposes to

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[a] `http://www.archeops.org`

[b] `http://astro.estec.esa.nl/Planck`

observe by night. Maximising integration time means going above the Arctic circle. After a test flight in Trapani (Sicily) with four–hours integration time, the upgraded instrument was launched three times from the Esrange base near Kiruna (Sweden) by the CNES in the last 2 Winter seasons. The last and best flight on Feb. 7th, 2002 yields 12.5 hours of CMB–type data (at ceiling altitude and by night) from a 19–hours total. The balloon landed in Siberia and it was recovered (with its precious data recorded on–board) by a Franco–Russian team with –40 deg.C. weather.

Results

After being calibrated with the CMB dipole (Smoot et al. 1992)[20], the FIRAS Galaxy or Jupiter emission (yielding effective beams of typically 12 arcminute FWHM), eight detectors at 143 and 217 GHz are found to have a sensitivity better than 200 μK_{CMB} in one second of integration corresponding to the stationary part of the noise. For a square pixel of 20 arcmin the average 1 σ sensitivity with all detectors combined per channel is 100 and 150 μK_{CMB} (0.04 and 0.06 MJy/sr) at resp. 143 and 217 GHz. It is 0.4 and 0.8 MJy/sr at 353 and 545 GHz. A large part of the data reduction was devoted to removing additional noises which come from the various thermal stages at frequencies $f \leq 0.03\,\mathrm{Hz}$, and atmospheric effects: an elevation systematic effect is seen below 0.1 Hz and the four frequencies are correlated between 0.1 and 1 Hz.

Fig. 1 shows an example of the unprecedented millimetre maps that are currently being produced. Benoît et al. (2003a)[2] and (2003b)[3] show the results of a first reduction of the data, which are summarized below. Only the best bolometer of each CMB channel (143 and 217 GHz) is used here. The data are cleaned and calibrated, and the pointing is reconstructed from stellar sensor data. Maps are produced along many Monte–Carlo simulated maps to account for the exact power spectrum of the various noises. The sky power spectrum above a galactic latitude of 30 °(free of foreground contamination) is deduced after subtracting the noise power spectrum with a MASTER–like approach (Hivon et al. 2002)[9]. The spectrum is shown in 16 bins ranging from $\ell = 15$ to $\ell = 350$ in Fig. 2 in comparison with a selection of other recent experiments and a best–fit theoretical model. Much attention was paid to the possible systematic effects that could affect the results. At low ℓ, dust contamination and at large ℓ, bolometer time constant and beam uncertainties are all found to be negligible with respect to statistical error bars. The sample variance at low ℓ and the photon

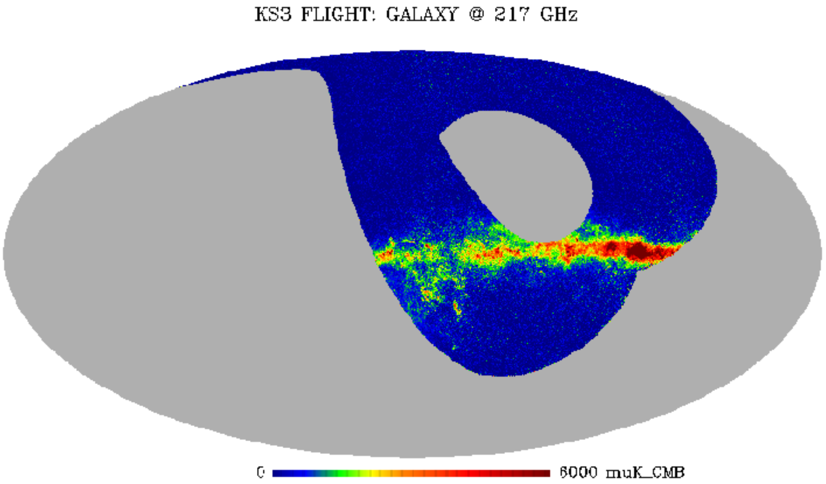

Figure 1. 217 GHz map obtained during the last ARCHEOPS flight. This is an all–sky Mollweide projection with the Galactic anticentre in the middle. This preliminary map is a combination of several detector outputs. To avoid 1/f noise in ARCHEOPS data, scales larger than 30 degrees were extrapolated from IRAS (Schlegel et al. 1998).

noise at high ℓ are found to be a large fraction of the final ARCHEOPS error bars in Fig. 2. One of the main goals of the experiment, *i.e.* 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, CBI, DASI, MAXIMA, VSA, has been achieved.

Cosmological constraints can be placed on adiabatic cold dark matter models with passive power-law initial fluctuations. Because ARCHEOPS power spectrum has small bins in ℓ and large ℓ coverage down to COBE scales, it provides a precise determination of the first acoustic peak in terms of position at the multipole $l_{\rm peak} = 220 \pm 6$, height and width. Using a large grid of cosmological models with 7 parameters, one can compute their likelihood with respect to the datasets. An analysis of Archeops data in combination with other CMB datasets constrains the baryon content of the Universe to a value $\Omega_{\rm b} h^2 = 0.022^{+0.003}_{-0.004}$ which is compatible with

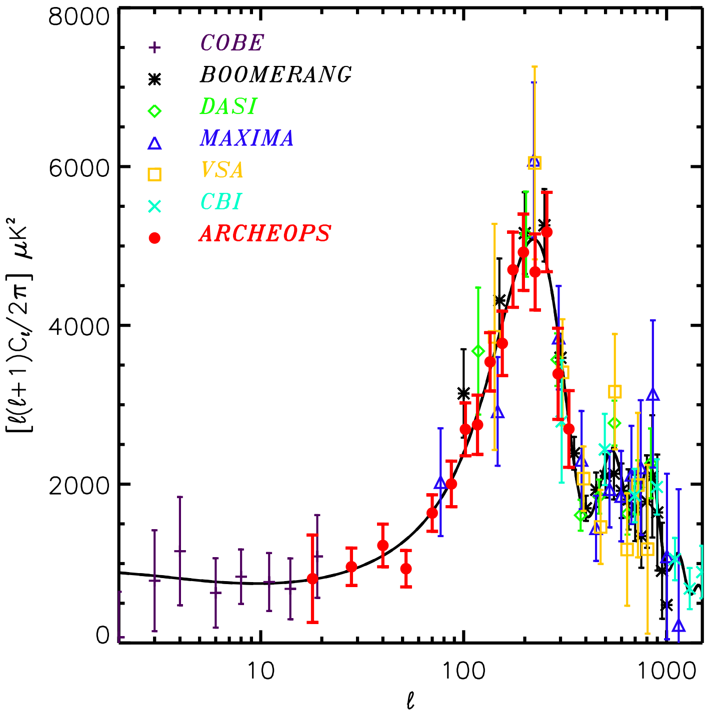

Figure 2. Archeops power spectrum in 16 bins along with some other recent experiments. A best model fit (continuous line) is obtained. The fitting allowed the gain of each experiment to vary within their quoted absolute uncertainties. Recalibration factors, in temperature, which are applied in this figure, are 1.00, 0.96, 0.99, 1.00, 0.99, 1.00, and 1.01, for Cobe (Tegmark et al. 1996), Boomerang (Netterfield et al. 2002), Dasi (Halverson et al. 2002), Maxima (Lee et al. 2001), Vsa (Scott et al. 2002), Cbi (Pearson et al. 2002) and Archeops (Benoît et al. 2003a) resp., well within 1 σ of the quoted absolute uncertainties ($<$ 1, 10, 4, 4, 3.5, 5 and 7%).

Big-Bang nucleosynthesis (O'Meara et al. 2001)[12] and with a similar accuracy (Fig. 3). Using the recent HST determination of the Hubble constant (Freedman et al. 2001)[5] leads to tight constraints on the total density, *e.g.* $\Omega_{\rm tot} = 1.00^{+0.03}_{-0.02}$, *i.e.* the Universe is flat. An excellent absolute calibration consistency is found between Cobe, Archeops and other CMB experiments (Fig. 2). All these measurements are fully compatible with inflation–motivated cosmological models. In particular, the best fit model shown in Fig. 2 is close to the mean likelihood Universe characterised by

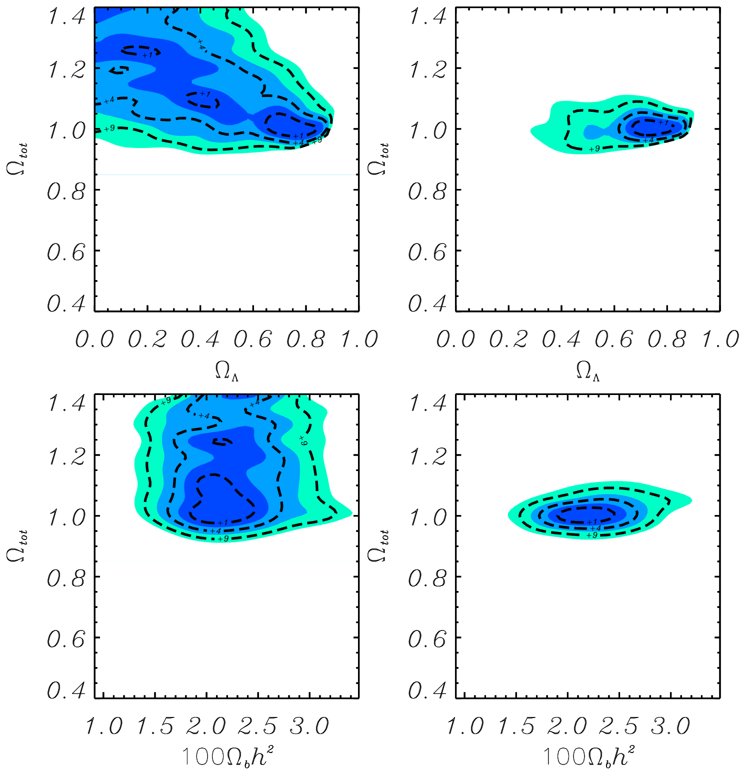

Figure 3. Likelihood contours between 3 of the cosmological parameters: baryonic density and cosmological constant in the abscissae and total density as the ordinate. Greyscale corresponds to 2–D limits and dashed line to 1–D contours with the Gaussian equivalent of 1, 2, and 3 σ thresholds. On the left, only the constraints from Archeops and other CMB experiments, identical to those in Fig. 2, are used. On the right panels, adding the prior on the Hubble constant $H_0 = 72 \pm 8\,$km/s/Mpc (68% CL, Freedman et al. 2001) reduces significantly the allowed values of the cosmological parameters.

$\Omega_{\rm tot} = 1.00^{+0.03}_{-0.02}$, $\Omega_\Lambda = 0.72^{+0.08}_{-0.06}$, $\Omega_{\rm b}h^2 = 0.021^{+0.001}_{-0.003}$, $h = 0.69^{+0.06}_{-0.06}$, $n = 0.96^{+0.02}_{-0.04}$, $Q = 19.2\,\mu$K, $\tau = 0$, obtained with Archeops and other CMB experiments and with the HST and $\tau = 0$ priors. Moreover, the constraints shown in Fig. 3 (right), leading to a value of $\Omega_\Lambda = 0.73^{+0.09}_{-0.07}$ for the dark energy content, is independent from and in agreement with supernovæ measurements (Perlmutter et al. 1999)[14] if a flat Universe is assumed.

Conclusions

Constraints on various cosmological parameters (Benoît et al. 2003b)[3] have been derived by using the ARCHEOPS data alone and in combination with other measurements. The measured power spectrum (Benoît et al. 2003a)[2] matches the COBE data and provides for the first time a direct link between the Sachs–Wolfe plateau and the first acoustic peak, 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 peturbations and a flat Universe assumption. Finally let us note that these results were obtained with only half a day worth of data.

Work is in progress to measure galactic dust emission polarization with the ARCHEOPS last flight data. 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.

Acknowledgments

We wish to thank ASI, CNES, and PNC for their continued support. Healpix package (Gorski et al. 1998)[6] was used throughout this work.

References

1. Benoît, A., Ade, P., Amblard, A., et al. , 2002, Astropart. Phys. 17, 101-124, astro-ph/0106152, `http://publi.archeops.org`
2. Benoît, A., Ade, P., Amblard, A., et al. , Astron. Astrophys., in press, 2003a, `astro-ph/0210305`
3. Benoît, A., Ade, P., Amblard, A., et al. , Astron. Astrophys., in press, 2003b, `astro-ph/0210306`
4. de Bernardis, P. et al. , Nature, **404**, 995, 2000
5. Freedman, W. L., Madore, B. F., Gibson, B. K., et al. , Astrophys. J., **553**, 47, 2001
6. Gorski, K. M. et al. , 1998 `astro-ph/9812350,` `http://www.eso.org/science/healpix`.
7. Halverson, N. W., Leitch, E. M., Pryke, C. et al. , Month. Not. Roy. Ast. Soc., **568**, 38, 2002
8. Hanany, S. et al. , Astrophys. J., **545**, L5, 2000
9. Hivon, E., Gorski, K. M., Netterfield, C. B., et al. , Astrophys. J., **567**, 2, 2002
10. Lee, A. T., Ade, P., Balbi, A. et al. , Astrophys. J., **561**, L1-L6, 2001
11. Netterfield, C. B. et al. , Astrophys. J., **571**, 604, 2002

12. O'Meara, J. M.; Tytler, D., Kirkman, D., et al. , Astrophys. J., **552**, 718, 2001
13. Pearson, T. J., Mason, B. S., Readhead, A. C. S., et al. , Astrophys. J., submitted, 2002, `astro-ph/0205388`
14. Perlmutter, S., Aldering, G., Goldhaber, G., et al. 1999, ApJ, 517, 565
15. Pryke, C. et al. , Astrophys. J., **568**, 46, 2002
16. Rubiño-Martin , J. A. et al. , Month. Not. Roy. Ast. Soc., submitted, 2002, `astro-ph/0205367`.
17. Schlegel, D. J., Finkbeiner, D. P., & Davis, M., Astrophys. J., **500**, 525, 1998
18. Scott, P. F., Carreira, P., Cleary, K., et al. , 2002, `astro-ph/0205380`
19. Sievers, J. L. et al. , Astrophys. J., submitted, 2002, `astro-ph/0205387`.
20. Smoot, G. et al. , Astrophys. J. Lett., **395**, L1, 1992
21. Tegmark, M., et al. , Astrophys. J. Lett., **464**, L35, 1996