Archeops: A balloon experiment to measure CMB anisotropies with a broad range of angular sizes

A. Benoît* and the Archeops Collaboration†

*Centre de Recherche sur les Très Basses Températures, 25 Avenue des Martyrs BP166, F–38042 Grenoble Cedex 9, France
†from the following institutes:
California Institut of Technology, Pasadena USA
Centre d’Etude Spatiale des Rayonnements, Toulouse France
Centre de spectrométrie nucléaire et de spectrométrie de masse, Orsay France
Collège de France, Paris France
DAPNIA CEA, Saclay France
Institut d’Astrophysique de Paris, Paris France
Institut d’Astrophysique Spatiale, Orsay France
Institut des Sciences Nucléaires de Grenoble, Grenoble France
IROE CNR, Firenze Italy
Jet Propulsion Laboratory, Pasadena USA
Laboratoire d’Astrophysique de l’Observatoire de Grenoble, Grenoble France
Laboratoire de l’accélérateur linéaire, Orsay France
Landau Institute of Theoretical Physics, Moscow Russia
Observatoire Midi-Pyrénées, Toulouse France
Queen Mary and Westfield College, London UK
Universita di Roma La Sapienza, Roma Italy
University of Minnesota at Minneapolis USA

Abstract. The Cosmic Microwave Background Radiation is the oldest photon radiation that can be observed, having been emitted when the Universe was about 300,000 year old. It is a blackbody at 2.73 K, and is almost perfectly isotropic, the anisotropies being about one part to 100,000. However, these anisotropies, detected by the COBE satellite in 1992, constrain the cosmological parameters such as the curvature of the Universe.

Archeops is a balloon-borne experiment designed to map these anisotropies. The instrument is composed of a 1.5 m telescope and bolometers cooled at 85 mK to detect radiation between 150 and 550 GHz. To lower atmosphere parasitic signal, the instrument is lifted at 32 km altitude with a stratospheric balloon during the arctic night. This instrument is also a preparation for the Planck satellite mission, as its design is similar.

We discuss here the results of the first scientific flight from Esrange (near Kiruna, Sweden) to Russia on January 29th 2001, which led to a 22% (sub)millimetre sky coverage unprecedented at this resolution.

THE SCIENTIFIC OBJECTIVE

The Cosmic Microwave Background

The Cosmic Microwave Background Radiation (CMBR) was emitted by the Universe when it was 300,000 years old just after the Big Bang. Its spectrum is known as a blackbody with a temperature of only 2.725 degrees above absolute zero. In various directions in the sky, we observe small temperature differences of the order of one part in 100,000, that were measured for the first time by the COBE satellite [9]. These so-called anisotropies trace the fluctuations of the density of matter that occurred before the decoupling of the CMBR. These fluctuations are thought to be the origin,
by gravitational collapse, of the large-scale structure of the Universe (galaxies, clusters,...) that we observe today. Its pattern can also yield an indirect measurement of the density, age and curvature of the Universe (see e.g. [5]).

There have been many experiments that have already measured these anisotropies with various techniques, angular resolution, noise and scanning strategy. Most recent ones (e.g. TOCO, Boomerang [2, 7], and Maxima [4, 6]) have improved on COBE results by the wavelength coverage, the sensitivity and the angular resolution.

The observation strategy

Balloon experiments are either limited by integration time due to small duration flights (in USA or Europe) or Sun disturbance (in Antarctic Summer). This in turn forbids mapping large portions of the sky. An alternative is to use a flight during the polar night in the more accessible Arctic region.

The Archeops experiment\(^1\) aims at mapping the anisotropies of the cosmic microwave background from small to large scales at the same time. For this purpose, a beam of about 8 arcminutes is swept through the sky by spinning a 1.5 m telescope pointing at 41 degree elevation around its vertical axis. A large fraction of the sky is covered when the rotation of the Earth makes the swept circle drift across the celestial sphere. This is only possible if the observations are done during the Arctic night and on a balloon where neither the Sun nor the atmosphere disturb the measurements. Ozone cloud emission and residual winds can be avoided with a high altitude stratospheric balloon.

From the Swedish balloon and rocket base in Esrange near Kiruna, in cooperation with Russian scientists, the CNES balloon team can launch balloons in the polar night, with a typical trajectory ending just before the Ural mountains in Russia. Integration times can be up to 24 hours in the December-January campaigns.

THE INSTRUMENT

A general description of the first Archeops instrument can be found in [1] where the first gondola used during the test flight (that happened in Trapani in July 1999) is described. The present experiment mainly uses the same concept.

The telescope, optics and detectors

The Archeops telescope is a two mirror, off-axis, tilted Gregorian telescope consisting of a parabolic primary (main diameter of 1.5 m diameter) and an elliptical secondary (this design is similar to the one proposed for Planck during phase-A). The telescope was designed to provide diffraction-limited performance when coupled to single mode horns producing beams with FWHM of 8 arcminutes or less at frequencies higher than 140 GHz. Both mirrors were milled from 8 inch thick billets of aluminum 6061-T6 and were thermally cycled twice during machining to relieve internal stresses. The primary and secondary mirrors weigh 45 kg and 10 kg respectively.

For CMB anisotropy measurements, control of spectral leaks and beam sidelobe response is critical. Archeops channels have been specifically designed to maximize the sensitivity to the desired signal, while rejecting out-of-band or out-of-beam radiation. We have chosen to use the configuration developed for Planck HFI, using a triple horn configuration for each photometric pixel, as shown schematically in Fig. 1.

In this scheme, radiation from the telescope is focussed into the entrance of a back-to-back horn pair. With no optical components in the path, control of the beam is close to ideal. Proper single mode corrugated feeds associated with a new profiled-flared design will be used to obtain 30dB telescope edge taper with the telescope/horns combination. The new profiled-flared horns avoid the use of a lens at the exit aperture of the second horn, creating a beam-waist where wavelength selective filters can be placed. Finally, the third horn maintains beam control and focuses the radiation onto the spider web bolometer placed at the exit aperture.

A convenient aspect of this arrangement is that the various components can be placed on different temperature stages in order to create thermal breaks and to reduce the level of background power falling onto the bolometer and fridge. In Archeops, the back-to-back horn pair is located on a cold plate cooled by Helium vapor at 8 K. Sidelobe response, beamwidth on the sky and spillover are accurately controlled by the design of the front horn. More low pass

\(^1\) More details on the experiment can be found at http://www.archeops.org
filters are placed on a screen at 1.6 K to further reject unwanted radiation from the inner sanctum where the 100 mK detectors are located.

Twenty two bolometers are placed on the 100 mK low temperature plate. There are 9 bolometers at 143 GHz, 7 at 217 GHz, 6 polarised bolometers at 353 GHz and two at 545 GHz. The higher frequency horns (545 GHz) are multimoded, as this increases the signal at this frequency and the side lobes rejection is less critical. One blind bolometer is placed on the same copper plate to study the electronic noise of the bolometers at this stage. These are placed at different points in the focal plane and observe the same sky pixel at a different time. Bolometers on the same line observe the sky with typically 100 msec time difference as bolometers on different lines observe the same pixel with a time difference of the order of a few minutes. The six 353 GHz channels are devoted to the measurement of galactic polarized emission. The bolometers are assembled in three pairs, with one single back-to-back horn and a polarizer splitter. The two bolometers of each pair measure the polarized intensity of the incoming signal in two orthogonal directions. Each pair makes a different angle with respect to the scan axis to enable the full determination of the Stokes parameters. Archeops will provide the first measurement of polarization in this range of frequencies with a sensitivity adequate for measuring galactic dust polarised emission, as well as a validation of the technical configuration for PLANCK-HFI.

The gondola and the pivot

The gondola is made with welded aluminium square tubes 30*30*2 and a careful design prevents from important deformations of the optical design in the presence of strength. Typical change in the relative mirror position stays below 0.2 mm when the gondola is lifted or tilted. Total mass of the main frame is 70 kg. The two mirrors and the cryostat are fixed to the frame and the elevation of the beam direction is fixed to the value of 41 degrees.

The pivot connects the flight chain of the balloon to the payload through a thrust bearing, providing the necessary degree of freedom for payload spin. Two deep groove bearings provide stiffness against transverse loads to the rotating steel shaft inside the pivot. The pivot includes a torque motor that acts against the flight chain to spin the payload. After initial acceleration, the motor provides just enough torque to compensate the friction in the thrust bearing and the small residual air friction.

The rotation of the payload is monitored by a vibrating structure rate gyroscopes that can detect angular speeds as low as 0.1 deg/s. These are sampled at 150 Hz by a 16 bit ADC and a PID feedback loop control is implemented in software, to drive the torque motor in the pivot.
The fast stellar sensor

A custom star sensor has been developed for pointing reconstruction in order to be fast enough to work on a payload rotating at 2-3 rpm. At this spin rate, the use of a pointed platform for the star sensor is impractical. Each independent beam (8 arcmin. wide) is scanned by the mm-wave telescope in about 10 ms, establishing a detector response time that excludes the use of present large-format CCDs.

We decided therefore to develop a simple night sensor, based on a telescope with photodiodes along the boresight of the mm-wave telescope. Thus, like the millimeter telescope, the star sensor scans the sky along a circle at an elevation of 41 deg.

A linear array of 46 sensitive photodiodes (Hamamatsu S-4111-46Q) were placed in the focal plane of a 40 cm diameter, 1.8 m focal length parabolic optical mirror. Each photodiode has a sensitive area of 4 mm (in the scan direction) by 1 mm (pitch in the cross-scan direction). The line of photodiodes is perpendicular to the scan and covers 1.4 degrees in elevation on the sky, with about 7.6 arcminute (along the scan) by 1.9 arcminutes (cross-scan) per photodiode. A top baffle, painted black inside and located above all nearby payload structures, prevents stray radiation.

The sensitivity of the photodiodes defines the average number of stars we can observe during one rotation of the payload. With a sensitivity limited to stars of magnitude 7, we can count between 50 and 100 stars per turn during nighttime. In order to control the pointing during the day, we use an optical filter in front of the diodes to minimize the perturbation due to stray light. A test flight in Kiruna (April 1999) shows that, even with the Sun at low elevation (< 5 deg. elevation) we can observe a few stars for each rotation of the gondola.

The star sensor software extracts from the time-sampled photodiode signals candidates star with detection time, measured flux, coordinate along diode array, and quality criteria. This software produces from raw data the list of time-ordered star candidates and makes it available for the second step of the software-reconstruction of the telescope pointing. The attitude reconstruction algorithm is based upon the comparison between star candidates and a dedicated star catalog. The fluxes of stars in catalog are computed from the Hipparcos catalog to simulate the star sensor spectral response.

The reconstruction is achieved using only star sensor data if the gondola spin axis motion is sufficiently slow. That was the case for the Trapani test flight. The precision of the pointing solution is better than 1 arcminute rms for the test flight. For the Kiruna 2001 flight, important speed variation of gondola rotation velocity required to use additional information from gyroscopes and GPS to recover a good association between signal and star catalog.

The cryogenics

The focal plane is cooled to 100 mK by means of an open cycle dilution refrigerator. This type of refrigerator has been designed for satellite applications (it will be used on Planck HFI) and Archeops is the first balloon-borne experiment using a dilution refrigerator. The dilution stage is placed in a low temperature box placed on the top of a liquid Helium reservoir at 4.2 K. The top part of this box contains the entrance horns and receives a significant amount of heat power from near infrared radiation (about 500 mW). Exhaust vapours from the helium tank maintain the horns near 7 K. The entrance is protected from radiation by two vapour cooled screens with openings for the input beam. The filters are placed on the horns at 7 K, on the 1.6 K stage (cooled by Joule-Thompson expansion of the dilution mixture) and on the 100 mK stage, just in front of the bolometers. The temperatures of each stage are monitored with thermometers: carbon resistance and NbSi metal insulation transition thermometers.

The bolometers are placed on the 100 mK stage supported by Kevlar cords. The dilution fluids (isotopic pure $^3$He and $^4$He) arrive through two small capillary tubes along a heat exchanger with the return mixture. The two capillaries join and the $^3$He is dissolved into the $^4$He, cooling down the mixture which is used to cool down the 100 mK plate using a small heat exchanger. We use two extra capillaries of larger diameter (0.5 mm) in order to precool the system by a circulation of $^4$He gas. These 5 capillary tubes (3 for dilution and 2 for precooling) and the electric wires (9 shielded cables with 12 conductors each) are soldered together, forming the continuous heat exchanger disposed around the 100 mK stage. Input flow is controlled by an electronic flow regulator. The output mixture is pumped with a charcoal pump placed inside the liquid helium (1 liter box filled with charcoal). During pre-launch operations, the output mixture is extracted with an external pump and the dilution stage can stay below 100 mK continuously for months. The hold-time of the cryostat is limited at 48 hours by the liquid helium tank of 20 liters. An electronic regulator is used to maintain constant pressure at one atmosphere in the helium tank.

In order to insure temperature stability of the bolometer a passive filter is used to thermalise the bolometer plate. The
open cycle dilution produces large temperature fluctuation $(100 \mu K/\sqrt{\text{Hz}})$ which we attenuate with a high specific heat material (HoY). Holmium has a Shottky anomaly around 200 mK which insures the high specific heat. Mixing it with Yttrium helps controlling the conductivity. By cooling down the bolometers through this thermal filter, a stability below a few $\mu K/\sqrt{\text{Hz}}$ was obtained during the flight.

The electronics

The bolometers are biased using AC square waves by a capacitive current source. Their output is measured with a differential preamplifier (the first stage uses JFET working at about 120 K) and digitized before demodulation. We use the boxes already designed in preparation for Planck HFI instrument. Each box can manage 6 bolometers and we used 6 of them for a total of 36 channels. All modulations are synchronous and driven by the same clock. This clock is also used for data readout, which is simultaneous for all bolometers and thermometers. Modulation parameters can be controlled by telecommand. Sampling of the raw signal is at 6.51 kHz before demodulation. Demodulation is performed by the EPLD and sampled twice per modulation period. We used a frequency of 76 Hz for modulation and 152 Hz for sampling. The on-board computer uses a transputer T805 and an 4 EPLD Altera 9400 to control all housetkeeping measurement, bolometer and star sensor data. The power supply consists of 39 batteries for electronics and satellite telemetry and 36 for the motor. All are 3 V and 36 Ah lithium batteries. With a total power of 150 W, this gives us about 48 h lifetime for the experiment.

The telemetry

After compression, the data are written to a storage module of 2 Gbyte Flash Eprom memory made of 256 circuits of 8 Mbyte each. A dedicated microprocessor is used to write the Eprom. To protect the data in case of bad landing, the data storage module is installed in a sealed box, pressurized at 1 atmosphere. The data are read after retrieval of the gondola. The compressed data are sent via the standard CNES telemetry (400 MHz) at the rate of 108 kbit/sec. This is possible only during the first phase of the flight (about 4 hours) when the balloon is in direct contact with the ground telemetry station. Another telemetry channel using the Inmarsat satellite is used to control the experiment during all the flight. We use the mini-M Inmarsat standard that allows a typical flow rate of 2 kbit/sec. A selected fraction of the data is sent through this channel to control the experiment and commands can be sent to correct all control parameters.

ARCHEOPS FLIGHTS AND FIRST RESULTS

A first flight of the instrument took place in Trapani on July 17th 1999. This test flight used only a few detectors (5) and we got only 4 hours of data during the night. Nevertheless, this flight allowed us to check all the fonctionnalities of the instrument [1].

Flight conditions at Esrange in 2000-2001 Winter

This Winter (December 2000 and January 2001), the polar vortex was not well positioned as the 2 previous winters and we did not get good flight conditions during the campaign. The wind conditions in the stratosphere gave us the possibility of a long flight only on December 1st, where the Archeops technical flight took place. Later on, we did not get good conditions before January 12th 2001 where we launched Archeops for a 7-8h flight. However, one of the flow-meter controlling the cryostat broke down 1 hour after take off and we had to abort the flight with a landing in Finland and a fast recovery without too much damage on the instrument. The next launch window opened on January 29th for a relatively short duration flight at an altitude of 32 km (too much wind at higher altitude) lower than the nominal 40 km.
The scientific flight

We finally were able to launch Archeops for its first scientific flight on the 29th of January, 2001. Because of the wind conditions we could only use a smaller balloon (150 000 m$^3$) otherwise the trajectory would have been too much North, endangering the recovery.

We had 7h30 of flight at float, with a temperature of the order of 90 mK on the focal plane almost all the way along. We decided not to fly too close to the Ural mountains: this would have been too risky for the recovery because of strong wind. The experiment was stopped (window closed and motor stopped) about one minute before the separation with the balloon occurred thanks to Inmarsat (00h26m30 LT). The gondola reached the ground at a latitude of 62.226 and a longitude of 53.341 (N-E of SyktYvkar).

Preliminary results

The first task after the flight is to reconstruct the pointing using the data from the stellar sensor. The residual error in pointing is given by the distribution of the declination difference between the reconstructed position and the stars. The present precision of the pointing solution for this flight is better than 2 arcminute rms.

To control the accuracy of the reconstructed pointing and extract the in-flight angular resolution of the detectors, their time response, and to calibrate the instrument on point sources, we use the signal of Jupiter measured in the bolometers and the pointing of each detector reconstructed from the Stellar Sensor. Jupiter is a bright source which is seen by one bolometer at a time thanks to Archeops scan strategy, we can therefore easily pinpoint its crossings (we could see it twice during the January 2001 flight).

If the pointing is accurate enough on the corresponding time periods, we can reconstruct the angular resolution as shown in Fig. 2, where the beam of one of the 217 GHz detector is represented as obtained on Jupiter: we found the FWHM of this particular beam to be of the order of 12.5 arcminutes, which includes the bolometer and electronics time response: the deduced optical beam is nominal at 8 arcminutes.

Since the response of the bolometers to Jupiter’s signal is a convolution of the intrinsic resolution of the back-to-back horns and the time response of the bolometer, we can also extract a measurement of both parameters: we typically found a time constant of the order of 5 to 15 ms, compatible with measurements on glitches (the intrinsic resolution of the horns being between 5 and 8 arcminutes).

As far as the calibration on point sources is concerned, we make use of the temperature of Jupiter [3] (T = 170 K). Taking into account its solid angle, we have extracted a calibration for each Archeops bolometers.

The 143 and 217 GHz channels are dominated by the cosmic dipole and some extra signal coming from the 10 K back-to-back horn emission (sinusoidal shape). At 545 GHz, the emission from the Galaxy is dominant as well as some atmospheric signal.

FIGURE 2. Jupiter as observed by one of the bolometers at 217 GHz. Azimuth-Elevation coordinates are in arcminutes. Note that the bolometer time constant spreads the signal a little on the left.
Flight at ceiling represents 7.5 hours worth of scientific data taken when the gondola was spinning at 2 rpm. The covered area corresponds to 22 percent of the whole sky. Fig. 3 shows a Mollweide projection in galactic coordinates (centered on the Galactic anticenter) of an extrapolation to the submillimetre of a combined IRAS-DIRBE map [8]. Due to the relative small duration (compared to 24h of one earth rotation), the area where the circles cross each other is very small. As a consequence, we had a relatively poor redundancy during this flight.

The galactic plane is well observed at all frequencies from Perseus to Cygnus regions. Some clouds much below the Galactic plane can easily be identified with their CO and infrared counterparts (Taurus, Pleiades, ...).

With the 353 GHz channels, Archeops will provide the first measurement of galactic polarized emission in this range of frequencies. It is first an important topic in the prospect of foreground removal for Planck-HFI, and is also of great interest to constrain the physics of galactic dust and molecular clouds.

Sensitivities are typically between 50 and 100$\mu$K$_{RJ}$ for one second of integration for one photometric pixel. There are about 8 pixels with a CMB sensitivity between 120 and 200$\mu$K$_{CMB}$ for one second of integration for one photometric pixel. This instrument is therefore very competitive with respect to other designs. Work is in progress to subtract all parasitic signals and extract the CMB fluctuation spectrum. Expected performances for the present flight are shown in Fig. 4. Good detections of the CMB anisotropy spectrum can be expected from low l to beyond the first acoustic peak.

CONCLUSIONS AND FUTURE FLIGHTS

Archeops is a balloon borne experiment dedicated to the measurement of the anisotropies of the Cosmic Microwave Background using the same technology as the Planck satellite will use. We were able to launch the instrument on the 29th of January 2001 at Esrange (Sweden). The flight lasted 7h30 at float, with all detectors working with nominal performances. This is a very important step in validating Planck-HFI concepts (Lamarre et al., this conference). The flight was unusually short due to strong winds in the stratosphere. We are currently analysing the data: reconstructing the pointing using the Stellar Sensor data, calibrating the instrument using point sources (Jupiter) as well as the dipole and the galaxy, and already some results are coming along such as maps of the galactic plane.

Nevertheless, because of the strong winds, the movements of the gondola induced a parasitic signal on bolometers which is different for each frequency. This makes the data analysis more difficult than planned. A flight at higher altitude (with a 400000 or 600000 m3 balloon) should permit to have a more stable experiment, with less atmospheric signal. In addition, to have a better measurement of the Cosmic Microwave Background, a longer flight (a 24 hour flight for instance or two flights with 12 hours each) should provide a larger redundancy on the sky. Expected sensitivity...
FIGURE 4. Sensitivity expected for the last Kiruna flight. The dotted curve shows a fiducial $C_l$ spectrum for a standard cosmology (in $\mu K^2$). The continuous line is the expected 1$\sigma$ error using the characteristics of the instrument during the flight (flat noise average and responsivity). The first dashed curve (on the left) shows the cosmic variance part of the noise and the second (on the right) shows the effect of detector noise.

shows that significant detections of the $C_l$ spectrum could be achieved between $l = 10$ to 1000. The large area covered by Archeops makes it a unique balloon instrument in lowering the CMB cosmic variance, the most important noise at $l$ below 100 (see Fig. 4). A new campaign is planned for the Winter 2001/2002, with two launch windows: one in December and one in January.

ACKNOWLEDGMENTS

We thank the CNES and Esrange Swedish Facility for their continued support for this project and the flights (technical and scientific) that were realised very smoothly.

REFERENCES

1. Benoît, A., et al., Astroparticle Physics, in press, astro-ph/0106152, 2001
2. de Bernardis, P., et al., Nature, 404, 955, 2000
3. Goldin, A. B., et al., Astrophysical Journal, 488, L61, 1996
4. Hanany, S., et al., Astrophysical Journal, 343, L3, 2000
5. Hu, W., Sugiyama, N., and Silk, J., Nature, 386, 37, 1997
6. Lee, A. T., et al., preprint, astro-ph/0104459, 2001
7. Netterfield, C. B., et al., Astrophysical Journal, submitted, astro-ph/0104460, 2001
8. Schlegel, D. J., Finkbeiner, D. P., Davis, M., Astrophysical Journal, 500, 525, 1998
9. Smoot, G. F., et al., Astrophysical Journal, 371, L1, 1991