PRELIMINARY RESULTS AND PERSPECTIVES IN THE ARCHEOPS EXPERIMENT

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Abstract
Observations of the Cosmic Microwave Background (CMB) temperature fluctuations are a powerful tool for testing theories of the early Universe and for measuring cosmological parameters. We present basics of CMB physics, review some of the most recent results and discuss their implications for cosmology. The Archeops balloon-borne experiment is designed to map the CMB with an angular resolution of 10 arcminutes and a precision of 30 μK per pixel. This will allow the measurement of the CMB fluctuation power spectrum from large to small angular scales. We describe preliminary results from the test flight which took place in July 1999 and present perspectives for upcoming scientific flights (January 2001).
1 Basics of CMB physics

Within the frame of Big-Bang theory, the Universe started about ten billion years ago in an extremely hot and dense phase. The dynamics of the Universe are governed by the Einstein equation that links the evolution of the space-time metric to the matter content of the Universe. Our Universe appears highly homogeneous and isotropic; this simplifies the metric to the so-called Robertson-Walker metric \[t,\] which depends on the scale factor of the Universe and its curvature which can be positive, negative or zero. The Einstein equations are simplified to the Friedman equations, which show that the Universe is expanding. The expansion can be eternal or not, depending on the value of the total matter density \(\Omega_m\) and the cosmological constant \(\Omega_\Lambda\).

Just after the Big-Bang, the temperature of the Universe was so hot that all the matter in the Universe was ionized. As the mean free path of photons in ionized matter is small, the photons were in thermal equilibrium with the baryons. The Universe was therefore optically thick. As it expanded, the temperature of the Universe cooled down and more and more electrons started to be captured by baryons. Because of the large photon to baryon ratio \(\approx 10^9\), the photons belonging to the high energy tail of the Planck distribution kept the matter ionized even after the temperature of the Universe dropped below 13.6 eV (160000 K). But when the temperature cooled down to 0.3 eV (3000 K), most of the matter in the Universe became neutral. This moment is known as recombination. As the Universe was no longer ionized, the photon mean free path became larger than the horizon, and the photons have not interacted with matter since. This is why this moment is also known as the matter-radiation decoupling.

Those photons that last scattered at this epoch have now cooled down to a temperature of 2.7 K (they were redshifted by a factor \(\approx 1100\)). They have a pure blackbody spectrum as they were at thermal equilibrium before decoupling. We see them as a homogeneous and isotropic radiation called the Cosmic Microwave Background (hereafter CMB). Their present density is about 412 photons.cm\(^{-3}\).

The CMB was discovered accidentally in 1965 by Penzias and Wilson \[1\] and was immediately interpreted as a relic radiation of the Big-Bang by Dicke and its collaborators \[2\]. Such a radiation had been predicted before by Gamow \[3\] and by Alpher and Herman \[4\] in 1948. This discovery was a major argument in favor of the Big-Bang theory. In 1992, the American satellite COBE discovered the first anisotropies in the temperature of the CMB with an amplitude of about 30 \(\mu K\) \[5\]. COBE also measured its spectrum with high precision \[6, 7\] proving
its pure blackbody nature. Such temperature fluctuations were expected, as they correspond to density fluctuations in the early Universe. We know that density fluctuations existed in the early Universe because a perfectly homogeneous Universe cannot lead to structure formation, galaxies, etc.

The CMB temperature fluctuations are commonly described using a spherical harmonic expansion (which is the analogue of a Fourier transform on the sphere):

$$\frac{\delta T}{T}(\theta, \phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \phi)$$  

(1)

where $\ell$ is the multipole index and is the analogue of the Fourier mode $k$ and $\ell$ is inversely proportional to angular scale (1 degree roughly corresponds to $\ell = 200$). The angular power spectrum of the temperature fluctuations of the CMB is defined as :

$$C_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2.$$  

(2)

The statistical distribution and the angular power spectrum of the temperature fluctuations of the CMB are predicted to be very different depending on whether these fluctuations arose from inflation or from topological defects. This gives us a tool with which to obtain information about the early Universe. In the case of inflation, one can derive the power spectrum as a function of the cosmological parameters\(^1\). Fig. 1 represents theoretical predictions for the angular power spectrum of the temperature fluctuations of the CMB for three different cosmological models (all of them suppose inflationary-like origins for the density fluctuations). The data point overplotted are from the most recent experiments. The first thing that appears when looking at the theoretical predictions for power spectra is that there are two different parts. The first part is at low values of $\ell$ (large angular scales) and exhibits no particular features. It is known as the Sachs-Wolf plateau. These large angular scales correspond to regions larger than the horizon at the time of decoupling. There has therefore not been any physical process coupling these regions since the end of inflation: the power spectrum is flat in this region. The second part of the power spectrum is the high $\ell$ region corresponding to angular scales smaller than the horizon at the time of decoupling (around $\ell = 200$). These regions have been in causal contact before decoupling and we expect physical processes to have occurred. The physical processes involved are acoustic oscillations in the photon-baryon fluid before decoupling: the baryons tend to collapse because of their gravitational interaction, but the photon radiation pressure does not allow any structure to collapse. There are

\(^1\)Freely available numerical codes, such as CMBFast\(^7\), have been developed for this purpose.
Theoretical predictions for the angular power spectrum of the anisotropies of the CMB (obtained using CMBFast for inflationary like models): for a critical (zero curvature) Universe with no cosmological constant (dotted line), for an open Universe with no cosmological constant (dashed line) and for a critical Universe with a dominating cosmological constant (dot-dashed line). The data points are from COBE, from BOOMERanG and from MAXIMA.

then a series of acoustic oscillations in the fluid (collapse leading to overdensities, expansion leading to underdensities and so on) involving larger and larger regions of the Universe as the horizon is increasing with time. This process ends when the photons decouple from the baryons, which are now allowed to collapse and form structures. Depending on the status (overdensity, underdensity or average density) of regions of the Universe of a given size, there will be peaks or valleys in the power spectrum. This effect is mitigated to some degree by the Doppler effect arising from the speed of matter in collapsing or uncollapsing regions at the moment of decoupling. The series of peaks we see in the angular power spectrum of the CMB are therefore called acoustic peaks and are just the result of these acoustic oscillations that happened in the photon-baryon fluid before decoupling.

The position and amplitude of the acoustic peaks (and particularly of the
first one, corresponding to the size of the sound horizon at the time of decoupling) as seen from here and now depend upon the values of the cosmological parameters. Basically, we are looking at regions of a given physical size located at redshift \( z \simeq 1100 \). The apparent angular size of these regions (where the acoustic peaks appear in the power spectrum) depends on the curvature of the Universe between \( z = 1100 \) and us which involves the cosmological parameters. For instance, a low density Universe would have a negative curvature so that the same physical size would be seen at lower angular size from a cosmological distance than in a critical density Universe. The first acoustic peak would therefore be shifted to larger values of \( \ell \).

This can be seen in Fig. 1 where the first acoustic peak for the dashed curve (low density Universe) occur at \( \ell \simeq 500 \) whereas it occurs at \( \ell \simeq 200 \) for the critical \( \Omega = 1 \) models (dotted and dash-dotted curves).

We see that the experimental data points from COBE confirm the theoretical predictions of a flat shape of the power spectrum at low \( \ell \) while the most recent experimental results on smaller angular scales (BOOMERanG and MAXIMA, two balloon-borne experiments) confirm the existence of a peak in the power spectrum at \( \ell \simeq 200 \), strongly favoring a flat (\( \Omega = 1 \)) Universe.

What can also be seen in Fig. 1 is that COBE concentrated its measurements on large angular scales (\( \ell \leq 20 \)) whereas the high resolution new experiments concentrate on small angular scales. This can be easily explained as COBE was a satellite that covered the whole celestial sphere with a very large beam (7 degrees FWHM), it could therefore only constrain the low \( \ell \) part of the power spectrum as larger values of \( \ell \) correspond to angular scales smaller than the beam. On the other hand, high resolution experiments like BOOMERanG or MAXIMA have a very small beam (less than 15 arcminutes FWHM) allowing the measurement of large values of \( \ell \) but they concentrate on a small part of the sky in order to obtain a large signal to noise ratio and a large redundancy. The Archeops experiment is intended to measure the CMB power spectrum from small to large values of \( \ell \) allowing to link COBE data to the first acoustic peak and beyond with a single experiment.

2 The Archeops experiment

Archeops is a balloon-borne experiment involving teams from France, Italy, UK and USA. The sky temperature is measured with cold bolometers and our scanning strategy allows us to cover a large fraction of the sky (25%). The instantaneous sensitivity and angular resolution of the Archeops experiment is similar the that of
the other balloon-borne experiments such as BOOMERanG and MAXIMA. The optical concept, read-out electronics and cryogenic system are very similar to what will be used for the bolometer instrument (High Frequency Instrument) on the PLANCK satellite\textsuperscript{2}. ARCHEOPS therefore both takes advantage of PLANCK developments and gives the opportunity to validate hardware, software and methods for PLANCK on real data.

The ARCHEOPS gondola hangs about 100 meters under a stratospheric balloon. The diameter of the balloon, at the cruise altitude of 40 km, is 120 meters. The gondola and the instruments are shown in Fig 2. The photons are first collected by the primary mirror (1 meter effective diameter) and then directed by the secondary mirror towards the horns, which are designed to filter the correct frequency bands and to focus the photons on the bolometers. During the flight, the gondola rotates at 3 revolutions per minute\textsuperscript{3} so that the beam draws large circles on the sky at a constant elevation (about 41\textdegree). As the Earth rotates, the part of the sky seen by the detectors slowly shifts in such a way that a growing fraction of the sky is swepted.

The detectors are spider-web bolometers\textsuperscript{4} \textsuperscript{15} at 4 different frequencies

\textsuperscript{2}PLANCK is an ESA satellite designed to make high precision measurements of the CMB fluctuations. The satellite will be launched in 2007.

\textsuperscript{3}The period will be 2 revolutions per minute for the scientific flights.

\textsuperscript{4}Bolometers with a spider-web shape designed to have a small effective surface in order to be
Archeops had a successful test flight in July 1999 between Trapani (Sicily) and Granja de Torre Hermosa (Spain). The focal plane contained 6 bolometers (one channel failed due to wiring problems) at 3 different frequencies: 143, 217 and 353 GHz. We obtained 4 hours of good quality night-time data covering 17% of the sky. The analysis of these data is in progress. A sample part of the time-ordered data we obtained is shown in Fig. 3. The voltage output of the bolometer (proportional to the temperature) is shown as a function of Universal Time for a few rotations of the gondola. The first thing we see is a large oscillation which is scan synchronous. Each rotation of the gondola corresponds to a period in the timeline. The bright and narrow peak seen at each rotation is due to Galactic plane crossing. This large amplitude is mainly a parasitic signal due to reflections from the balloon and is lower at lower frequencies. This parasitic signal will have to be removed before any CMB extraction.

The response of our instrument to a point source (shape of the beam) has been measured inflight on Jupiter. The angular size of Jupiter (less than 1 arcminute) is much smaller than our resolution so that it is effectively a point source for our instrument. The image we obtain from Jupiter is then the convolution of its true profile on the sky (a Dirac peak) by the instrumental response. It is therefore a map of our effective beams. These maps are shown in Fig. 4 represented at their respective position in the focal plane (also measured with Jupiter). The beam widths all turn out to be smaller than 13 arcminutes, except for bolometer 3-6 which is very elongated in the cross-scan direction and exhibits a double peak. This is not surprising as for this channel the feed horn was not corrugated. Moreover, Jupiter’s brightness temperature is known with an accuracy of about 5%, allowing us to perform a point source calibration.
Figure 4: Beam shapes measured on Jupiter represented at their respective position within the focal plane. Bolometer 1-1 (middle) and 1-3 (bottom) are at 143 GHz, bolometers 2-4 (top) and 2-5 (right) are at 217 GHz and bolometer 3-6 (left) is at 353 GHz. Bolometer 2-5 exhibits a much larger amount of high frequency noise than the others (due to wiring problems) and will not be used for analysis. The + signs indicate theoretical pre-flight positions and the × signs indicate the fitted Gaussian center for each bolometer.

In Fig. 5, we show the reprojection of our data on the celestial sphere (after low frequency drift removal using Fourier filtering on the timelines). The effect of the parasitic signal is clearly visible. To remove this parasitic signal, we developed a method based on the fact that it is correlated between different frequency bands (it is higher at higher frequencies). The 353 GHz channel is then used as a tracer of the parasitic signal. The right panel of Fig. 5 shows the map obtained after decorrelation of this effect. The large remaining gradient is that part of our data correlated to the dipole (due to the Doppler effect of our motion with respect to the CMB frame). The dipole is an extended source with very well known temperature and can therefore be used for calibration.

Besides the estimation of cosmological parameters, CMB experiments produce maps of the sub-millimeter sky that are of high interest for Galactic astronomy and for cosmology. We obtained with the Archeops flight test the highest resolution maps of the galactic plane at 353 GHz. A preliminary map of the Galactic plane is
Figure 5: Direct reprojection of the data (143 GHz channel, low frequency drifts removed) on the celestial sphere (left panel). The right panel shows (with the same color scale) the data after parasitic signal decorrelation (using the 353 GHz channel as a tracer of the parasitic signal). The dipole is now clearly visible and can be used for calibration. The pixellisation used for these maps is HEALPix [10].

shown in Fig. 3 and is now under study. High latitude sources can be already seen in this preliminary map.

3 Conclusions and perspectives

Archeops had a successful test flight last summer and produced 4 hours of high quality data (with 4 bolometers) on 17% of the sky. The angular resolution achieved during the test flight was better than 13 arcminutes and we expect it to be 10 arcminutes for future flights. The experiment will fly this winter from Kiruna, Sweden yielding at least 24 hours of night-time data with 24 bolometers in 4 frequency bands and a sky coverage of 25%. This future flight will provide us much more data than the test flight allowing a better estimation of the systematic effects (parasitic signals, temperature drifts ...).

With a very large ratio between sky coverage and angular resolution, Archeops will provide high quality maps of the CMB sky (≃ 400000 independent pixels) allowing a precise measurement of the CMB angular power spectrum from large angular scales (ℓ ≃ 10) to small angular scales (ℓ ≃ 800). Measuring the power spectrum over such a large range will allow us to measure the cosmological parameters with high precision and to start constraining the physics of the early Universe.
Figure 6: Preliminary map of the galactic plane in the Archeops 353 GHz channel (850 microns wavelength) This is the highest resolution map at this frequency. Bright sources can already be seen at high galactic latitude.

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