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From BOOMERanG to B-B-Pol

Balloon-borne observations of cosmic microwave background polarization

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Abstract. Balloon experiments have played and will play a pivotal role in the study of the Cosmic Microwave Background (CMB), the fossil radiation coming from the early universe. The BOOMERanG experiment has measured the anisotropy (1998-2002) and the E-mode polarization of the CMB (2003-2006), while a new flight of BOOMERanG is planned to measure the polarization generated by interstellar dust at high galactic latitudes. This information is necessary in view of future satellite experiments aimed at a measurement of the B-mode polarization in the CMB. The B-B-Pol experiment is aimed at measuring the polarization of the CMB at large angular scales, using long duration balloon flights during the polar night. This experiment will validate several of the experimental methods to be used in the future B-Pol satellite mission.

Key words. Stars: abundances – Cosmology: Cosmic Microwave Background – Cosmology: observations – Stratospheric Balloons

1. Introduction

Observations of the Cosmic Microwave Background have provided detailed views of the Universe at the recombination epoch, at redshift ∼ 1100. In the CMB anisotropy maps from BOOMERanG (Masi et al. 2006), due to the extreme sensitivity of cryogenic bolometers operated at balloon altitude, a noise of $\sim 20\mu K$ for each 3.5' pixel has been achieved. The consistency of the maps from independent experiments (for example BOOMERanG and WMAP), working at different frequencies and with very different measurement methods, is the best evidence that the faint structure observed is not due to instrumental artifacts (Masi et al. 2006). Moreover, it has exactly the spectrum of CMB anisotropy, which means that it is not due to foreground emission. So we can conclude that everything we see in these maps results from structures present in the Early Universe, and from effects on light propagation along the path from that early epoch to our telescopes. The image of the CMB thus depends on the physics of the very early universe (initial conditions), on the physics of the Universe during the plasma era (photons-baryons acoustic oscillations), and on the geometry of light propagation, i.e. on the geometry of the universe at large scales.

We expect that the characteristic scale of the acoustic horizon is imprinted in this image. Since this linear scale can be computed from first principles, we can carry out an angular size test on the image of the CMB, thus deriving the density parameter. This and other cosmological parameters are best estimated by means of a power spectrum analysis of the maps of the CMB (de Bernardis et al. 2002). This method has been so successful that nowadays we have a minimalist model fitting the angular power spectrum of the CMB and a number of other cosmological observations (the abundances of primordial light elements, the recession of galaxies, the fluxes of high redshift SN1a candles, the large-scale distribution of galaxies and the distribution of Ly-α clouds...). The model has only 6 parameters (the Hubble constant H_o, the density of baryons Ω_b, the density of matter - including dark matter - Ω_m, the density of Dark Energy Ω_Λ, the spectral index of the power spectrum of primordial density perturbations n_s, and the mass power spectrum normalization σ_8), and works remarkably well from an empiric point of view (see e.g. Tegmark et al. 2004). There are, however, three main enigmas in the current scenario: the nature of dark matter, the nature of dark energy, and the origin of the universe itself and of its structure. In the following we will focus on the third one, and will show how balloon-borne missions can help in solving the enigma of the origin of cosmic structures, through detailed observations of the polarization of the CMB.

2. CMB Polarization measurements

CMB photons are Thomson-scattered by electrons at recombination. Linear polarization in the scattered radiation is obtained if there is a quadrupole anisotropy in the incoming, unpolarized photons (Rees 1968). This can be produced in two ways. The first, unavoidable source of quadrupole anisotropy of the photon field is the density fluctuation field present at recombination. Density fluctuations induce peculiar velocities in the primeval plasma. For this reason a given electron receives redshifted or blueshifted radiation from the surrounding electrons. Where there is a velocity gradient, a quadrupole anisotropy in the radiation is generated, and the scattered radiation is polarized. So the measurement of the polarization of the CMB probes the velocity field present at recombination. This effect, due to scalar fluctuations, produces a non-rotational polarization field (called E-modes of CMB polarization). The E-mode polarization spectrum EE (and its correlation with the anisotropy TE) can be computed very accurately from the density fluctuations inferred by the measured anisotropy spectra. A signal of the order of a few μK rms is expected for an experiment with angular resolution better than 1^o. The power spectrum of this signal has maxima where there are minima in the anisotropy power spectrum, just because in a density oscillation there is maximum velocity when the density is equal to the average, while there is zero velocity when the density fluctuation is maximum. The second source of quadrupole anisotropy at recombination is the presence of long wavelength gravitational waves. If, as expected in the inflationary scenario, a stochastic background of gravitational waves is generated in the very early universe, then we should be able to see an additional component of the polarization field. The amplitude of this component is very small (100 nK or lower, depending on the energy scale of inflation), but this has also a curl component (B-mode, BB). Using proper analysis methods, the B-mode inflationary component can thus be disentangled from the dominant E-mode, opening a unique window to probe the very early universe and the physics of extremely high energies (around 10^{16} GeV) [see e.g. (Dodelson 2003)].

BOOMERanG was the first instrument to produce images of the CMB with resolution and sensitivity good enough to show the sub-degree structure of acoustic horizons at recombination. We published multi-frequency maps of 3% of the sky, with 10' FWHM resolution (de Bernardis et al. 2000). From these, accurate angular power spectra of the CMB (l=50-1000) were computed (Netterfield et al. 2002; de Bernardis et al. 2002; Ruhl et al. 2003), showing the presence of three acoustic peaks at l = 210, 540, 845, due to the acoustic os-

Fig. 1. Launch of the BOOMERanG experiment in Antarctica (Jan.6th,2003)

cillations of the photon-baryon plasma. From these spectra, cosmological parameters were derived (Lange et al. 2001; de Bernardis et al. 2002; Ruhl et al. 2003). We found that the geometry of the universe is very nearly flat ($\Omega_o = 1.03 \pm 0.04$); that the fluctuations derive from a primordial density power spectrum nearly scale invariant ($n_s = 1.02 \pm 0.07$): two predictions of the inflationary scenario fully confirmed. Moreover, we found that the density of baryons is $\Omega_b h^2 = 0.023 \pm 0.003$, perfectly consistent with the predictions of the Big Bang Nucleosynthesis scenario tested from the measurement of primordial abundance of light elements. The same density of baryons is required in the nucleosynthesis process, in the first three minutes after the Big Bang, and 380000 years later, during the acoustic oscillations of the primeval plasma. This fact strongly strengthens the general autoconsistency of our early universe model. We also investigated the Gaussianity of the CMB maps by means of Minkowski functionals, Bispectrum, Trispectrum (Polenta et al. 2002; De Troia et al. 2003, 2007). In parallel, using the ancillary measurements at 410 GHz, we have shown that the contamination form interstellar dust is less than 1% of CMB Power Spectrum at 150 GHz (Masi et al. 2001). The dual experiment MAXIMA, flown from Palestine (TX), produced almost at the same time as the first BOOMERanG results a CMB map statistically consistent with the BOOMERanG one. The power spectra obtained from the two experiments were also statistically consistent, giving even higher reliability to the measurement (Hanany et al. 2000; Lee et al. 2001).

The BOOMERanG payload has been modified in 2002 to make it sensitive to the polarization. Polarization sensitive bolometers have been custom developed (Jones et al. 2003), and an improved attitude reconstruction system based on a steerable star-camera was used. All the details of this instrument, flown in 2003 (see fig.1), and of the produced maps are reported in(Masi et al. 2006) . In (Jones et al. 2006; Piacentini et al. 2006; Montroy et al. 2006) we reported the measured TT, TE and EE spectra. While both TE and EE are detected with high significance, BB is not detected, and the precision of the other spectra is not sufficient yet to constrain the cosmological parameters better than anisotropy measurements (Mac Tavish et al. 2006). This situation is common to all the CMB polarization measurements to date (see e.g. (Readhead et al. 2004; Leitch et al. 2005; Barkats et al. 2005; Page et al. 2006; Ade et al. 2007)). A noticeable exception is the measurement of the optical depth of reionization, estimated from the large-scale polarization of the CMB better than from anisotropy measurements (Page et al. 2006).

Considerable effort is being spent by CMB experimentalists to prepare high accuracy and sensitive experiments to detect the rotational component of CMB polarization. There are three big issues to be solved for this measurement:

• Detector noise : the signal we are looking for is in the 1-100 nK range. Successful

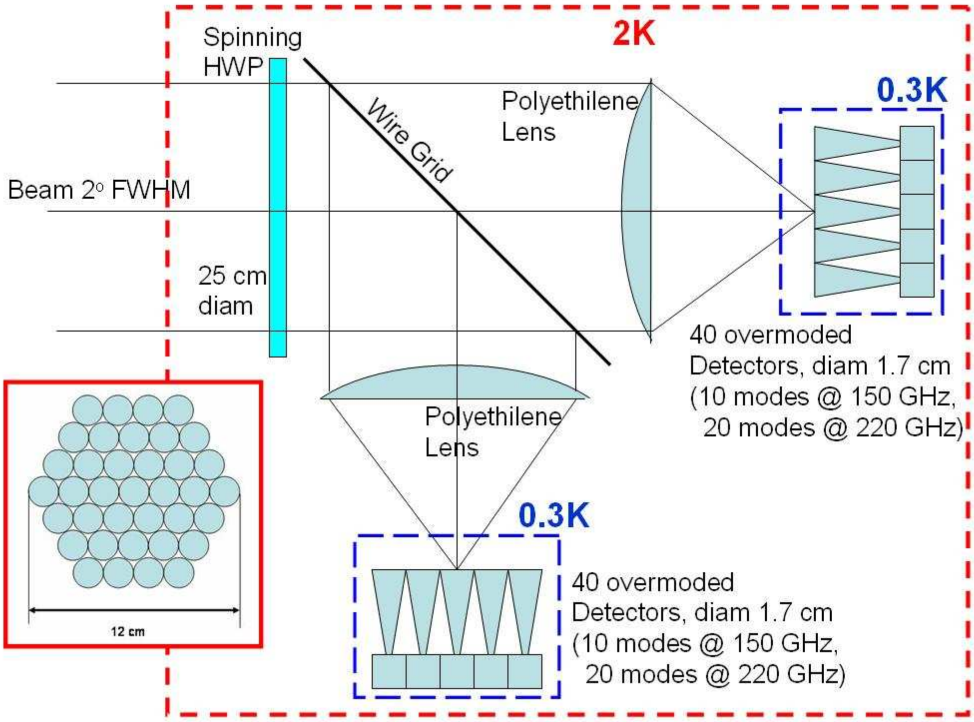

Fig. 2. Concept diagram of the High Frequency Instrument for B-B-Pol . In the box, a front view of the detector array, consisting of 37 detectors per channel, is shown. The size of the array does not require a very large cryostat.

polarization surveys to date have reported measurements of signals of the order of 2 μK rms. Since cryogenic bolometers are already close to be limited by photon noise of the CMB itself, the 100x improvement in sensitivity can only be obtained increasing the number of detectors, i.e. by developing large-format arrays of microwave detectors. Different technological solutions are competing: Transition Edge Sensor bolometers with SQUID readout are the most advanced, and important scientific results are already being produced (Halverson et al. 2008). Cold Electron Bolometers and Kinetic Inductance Detectors are also improving at high speed. Coherent detectors also have been compactly packaged to build large focal planes. The likelihood to detect the primordial gravitational waves for different levels of noise has been estimated in several papers (see e.g. (Pagano et al. 2007)). However, the real difficulty is to solve simultaneously also the other issues listed below.

• Systematic Effects : this is a real nightmare. The signal to be detected is so much smaller than detector noise that it is very difficult to detect low level systematics. Current polarization experiments have managed to keep the systematic effects below about 0.1 μK. Here we want to improve this by a factor around 100. The only way to improve here is to experiment. New polarization modulators and optical components must be characterized with unprecedented accuracy. Enough to keep the experimentalists busy for years with laboratory developments and ground-based and balloon-borne experiments.

• Polarized Foregrounds. Our galaxy emits polarized radiation: elongated interstellar grains, aligned by the Galactic magnetic field, produce thermal emission with a few percent polarization degree(Ponthieu et al. 2005); radiation emitted by the electrons of the interstellar medium spiralizing in the Galactic magnetic field produce highly polarized synchrotron radiation. A first survey of this emission has been carried out by the WMAP satellite (Page et al. 2006). The level of total polarized emission is up to 100 times larger than the goal polarization signal from primordial gravitational waves. It is thus necessary to characterize the polarized foreground at the 1% level.

The EBEX balloon-borne instrument (Oxley et al. 2004) aims at detecting the B-modes by means of a high resolution (< 8') telescope and large-format arrays of bolometers working at 150, 250, 350, 450 GHz. The polarization is modulated by an achromatic rotating half wave plate: a technique pioneered by the MAXIPOL experiment (Johnson et al. 2006). The instrument is to be flown on a long-duration balloon in Antarctica.

SPIDER (Mac Tavish et al. 2006; Crill et al. 2 008) is devoted to large-scale measurements of CMB polarization, obtained with cryogenic bolometers covering the spectral range from 80 to 270 GHz. A large fraction of the sky is observed during an ultra-long duration balloon flight. The instrument is a precursor of the EPIC CMB Polarization satellite, studied in the framework of the NASA Beyond Einstein program (Bock et al. 2006).

On the European side, in the framework of the Cosmic Vision ESA program, the B-Pol satellite has been proposed (B-Pol 2007). B-Pol is based on a set of refractive telescopes (one per band, from 45 to 350 GHz), each with its own wave-plate polarization modulator and its bolometric detector array. Though B-Pol was not selected for the first round of Cosmic Vision missions, the importance of the CMB polarization science and the necessity to carry out all the technological developments for this experiment have been stressed by ESA, in view of the next round of calls.

3. B-B-Pol

A set of preliminary balloon flights (named B-B-Pol, for Balloon B-Pol) will be used to develop and validate the involved technologies, and, most important, to detect systematic effects related to the measurement, validating mitigation strategies. The scientific target of B-B-Pol is to explore the low-ℓ region of the CMB polarization angular power spectrum, $\ell \lesssim 50 - 100$. This region is very difficult to explore from ground due to the variability of the atmosphere at large scales, especially at high frequencies ($\nu \gtrsim 100GHz$). The final measurement has to be done from space, but a balloon measurement can already produce significant results. The first issue is sensitivity. With current technology, a long-duration balloon flight will last from 2 to 4 weeks. Even longer flights have been carried out by NASA in Antarctica, during the Antarctic summer. However, a large-scale measurements needs to cover a very large fraction of the sky, which means a polar night flight. Balloons have been flown during the Arctic polar night (for example CNES has flown Archeops for a 2-days flight), so the technology is mature to attempt long duration flights in the polar night. The Italian Space Agency with Andoya Rocket Range is developing the Svalbard site for polar flights (see the contribution of S. Peterzen in these proceedings), and a test polar night flight will be tried soon. This will give us a definitive confirmation of the feasibility of long duration balloon flights around the north pole during the polar night.

Assuming that polar night flights are feasible, we have designed B-B-Pol as a spinner, rotating at constant speed in azimuth. If the detector beams are oriented at an elevation of 30 to 45 degrees, a large fraction of the northern hemisphere can be scanned every day of the mission, in an extremely cold and stable environment.

For the high frequency instrument, we have considered a multi-pixel polarimeter arranged as in fig.2

The incoming radiation is modulated by the assembly of a rotating HWP and a wire grid polarizer. There is no other optical com-

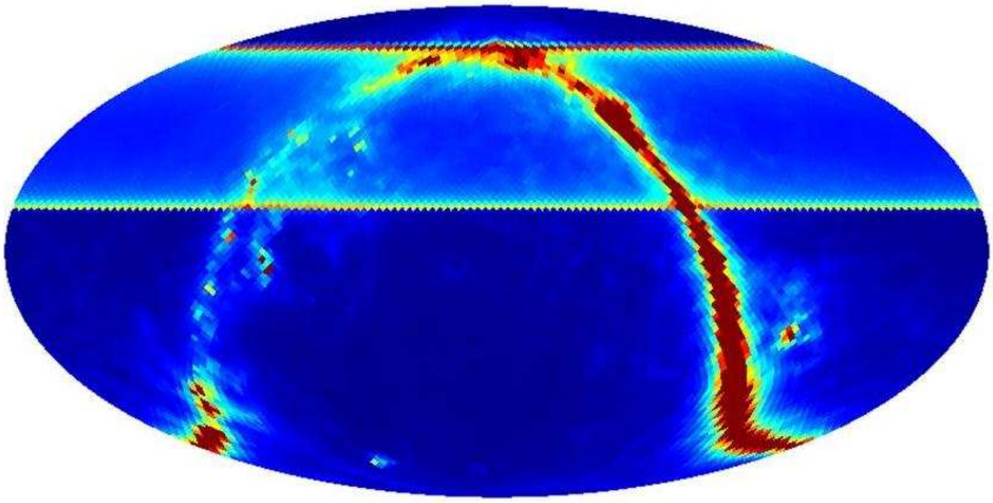

Fig. 3. Sample sky coverage in equatorial coordinates achievable in a single 14 days flight during the polar winter. The region observed by the experiment is the lighter horizontal band at declinations between 23^o to 77^o. The background map is extrapolated from the IRAS 100 μ survey, and represents the brightness of interstellar dust.

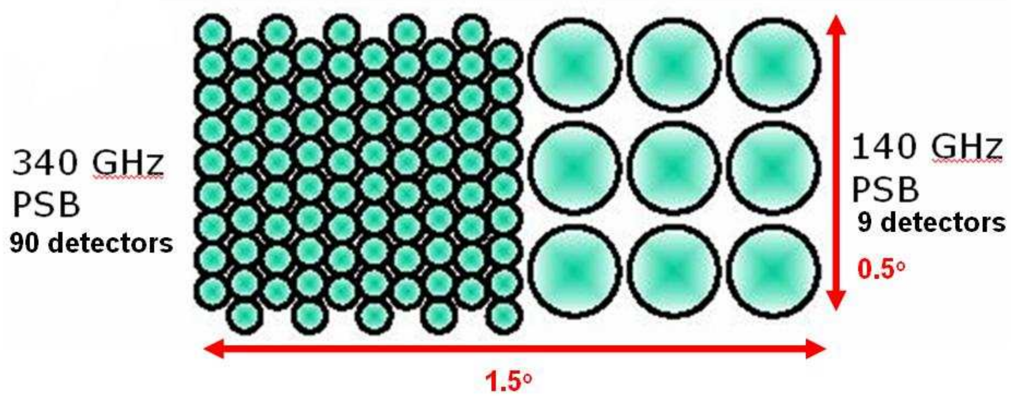

Fig. 4. Sketch of the BOOMERanG-FG focal plane. The experiment is aimed at measuring the polarization of interstellar dust at high galactic latitudes at 350 GHz, a frequency very close to those used to measure CMB polarization.

ponent in front of the system, so that the polarization purity depends entirely on the quality of the HWP and only slightly on the polarization properties of the horns in the detector array. The main feature of the detection system is the use of bolometers feeded by multimoded horns. With respect to single-mode detectors, this approach increases the sensitivity of the instrument by a significant factor at the expense of a lower angular resolution, which is not needed for the target of this instrument. Worksheet calculations show that a sensitivity of the order of 10 $\mu K/\sqrt{Hz}$ can be reached both at 140 GHz and at 220 GHz for each detector of the array. In fig.3 it is shown a sample sky coverage achievable in a single two weeks flight during the polar winter. Using this simulation, it can be shown that the measurements of the reionization peak in the polarization power spectrum at $\ell \sim 6$ are limited by cosmic variance for $r \sim 0.01$.

In addition to this already important scientific target, B-B-Pol will be used to test key technologies required by ESA to achieve undisputable technology readiness for the new Cosmic Vision Call. As evident from fig.2 the high frequency instrument polarimeter will use a rotating half wave plate (HWP) / polarizer assembly to modulate the linear polarization from the sky. As in B-Pol, this requires a high-quality HWP (see e.g. Pisano et al. (2006); Savini et al. (2006)) and a low power, high speed cryogenic rotator (see e.g. Hanany et al. (2003)). This system is crucial to the success of the satellite mission, and will be fully developed and tested in the balloon B-B-Pol .

4. BOOMERanG-FG

The new flight of BOOMERanG is devoted to the measurement of the polarized brightness of interstellar dust at high galactic latitudes, in a band centered at 350 GHz. This frequency has been selected because it very close to the optimal bands to measure CMB polarization (50-220 GHz): the extrapolation of the interstellar dust polarization to CMB frequencies is thus more accurate than from high frequency surveys. The focal plane of BOOMERanG-FG is sketched in fig.4. The baseline detectors for this mission are cold electron bolometers developed in Chalmers (Kuzmin 2007). The rest of the payload is very similar to the one described in Masi et al. (2006). In a long duration summer flight from Svalbards, we plan to carry out a deep survey of $\sim$ 400 square degrees region at high galactic latitudes (center at RA$\sim 16^h$, dec$\sim 40^o$) and a survey of $\sim$ 1000 square degrees in the galactic plane (center at RA $\sim 20.7^h$, dec$\sim 40^o$).

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