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BOOMERanG

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Abstract. The BOOMERanG experiment is a balloon-borne microwave telescope devoted to measurements of anisotropy and polarization of the Cosmic Microwave Background Radiation (CMB). The instrument is multiband in order to map the CMB and have a good understanding of all the important contaminating signals, (mainly galactic), and remove them if needed. Observations are carried out at about 38 Km of altitude, during a circum-antarctic Long Duration Balloon flight provided by NASA-NSBF. After two test flights in 1997, the instrument has been flown as a long duration payload in 1998 (covering four bands at 90, 150, 240, 410 GHz), and in 2003 (covering three bands at 150, 245, 345 GHz with polarization sensitive bolometers). Data from the first Antarctic flight are now fully analyzed; data analysis of the second (polarization) flight is currently under way.

Key words. Cosmology, Cosmic Microwave Background, Antarctic Astronomy

1. Introduction

The BOOMERanG experiment has proven to be extremely efficient in producing sensitive maps of the sky in the mm/submm wavelength range. This range is the last "Terra Incognita" of the exploration of the sky. In fact atmospheric transmission is

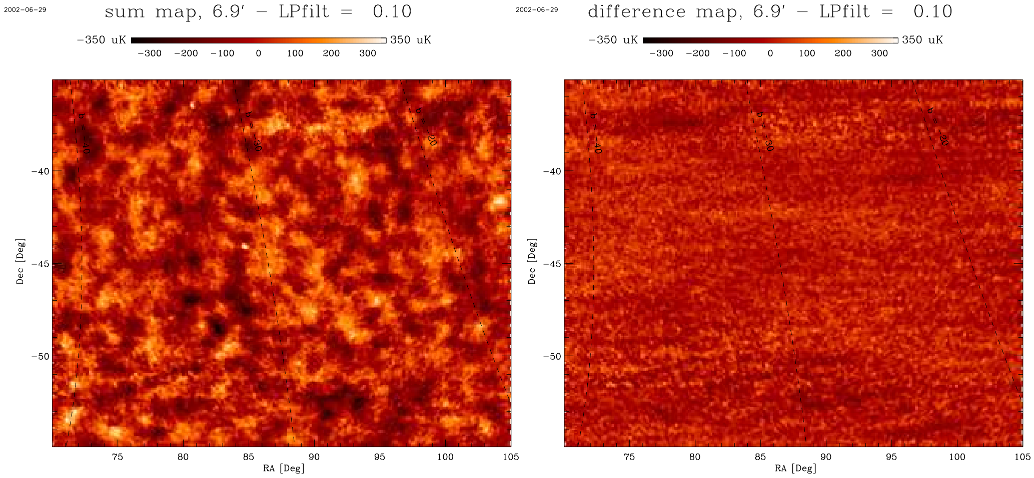

Fig. 1. Comparison of maps obtained from two different channels at 150 GHz. In the left panel: sum of the two maps; In the right panel: difference of the two maps. The difference map is dominated by noise, at a level much smaller than the sky structure evident in the sum map.

quite poor in this range, and its emission is much larger than any sky signal: it is almost impossible to carry out sensitive measurements from ground, unless the very best site (cold, dry, stable) is used. The first full sky survey in this range will be from the Planck (ESA) satellite in 2007. Meanwhile, balloon borne experiments provide a relatively fast and cheap approach to selected targets. BOOMERanG has produced maps of about 3% of the sky which can be considered good pathfinders on this research line. The main scientific results to date can be summarized as follows: • Cosmology results: 1) first maps of the CMB anisotropy where sub-horizon structures are visible with good signal to noise ratio. 2) Angular power spectrum of the CMB: detected the presence of three peaks, the signature of acoustic oscillations happening in the primeval plasma. 3) Measure of the cosmological parameters Ω, n_s, Ω_b, with unprecedented accuracy. 4) Accurate estimation of the gaussianity of the CMB temperature maps. 5) Statistical detection of clusters of galaxies by means of the Sunyaev Zel'dovich effect. • Astrophysical results: 1) Detection of Interstellar (cirrus) dust at high galactic latitudes, at all frequencies from 410 GHz down to 90 GHz. 2) Measurement of the angular power spectrum of the interstellar cirrus emission; dust contamination at 150 GHz is less than 1% of the CMB anisotropy power spectrum at high galactic latitudes. 3) Maps / photometry of galactic / extragalactic sources.

2. The 1998 instrument

BOOMERanG is the result of merging several advanced technologies: spider-web bolometers (developed at JPL and Caltech); quasi-Total-Power bolometer readout (developed at Caltech); high quality band-defining filters (developed in Cardiff); long duration cryogenics at 0.3 K (developed in Rome La Sapienza and ENEA-Frascati); low sidelobes off-axis telescope (developed in Rome); attitude control system (developed at IFAC-CNR

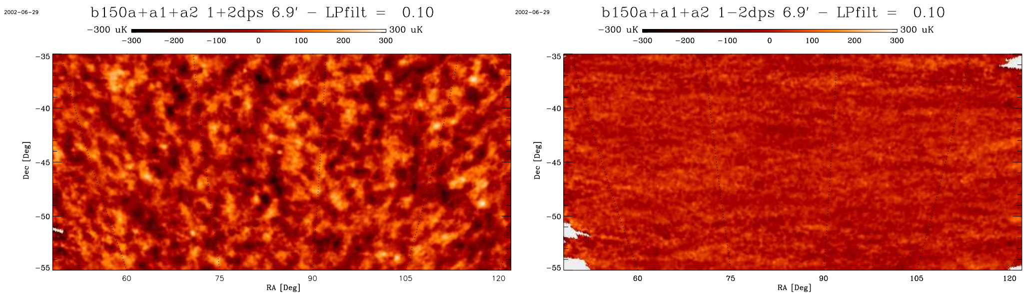

Fig. 2. Comparison of maps obtained from 1 dps scans and from 2 dps scans. In the left panel: sum of the two maps; In the right panel: difference of the two maps. The difference map is sensitive to instrument related effects, and is dominated by noise, at a level much smaller than the sky structure evident in the sum map.

in Florence). Details on the instrument can be found in Mauskopf et al. (1997), Masi et al. (1998), Masi et al. (1999), Piacentini et al. (2002), Crill et al. (2003).

3. The maps from the 1998 flight

During 190 hours of the 260 available we scanned the high galactic latitude region where we expected the lowest contamination from interstellar dust emission. The region is located in the constellations of Caelum, Doradus, Pictor, Columba, Puppis. The low frequency component of the signal has been removed in the payload electronics and in the process of map making, in order to get rid of most of the 1/f noise. As a result, the maps do not contain angular structures larger than 10 degrees, being effectively high pass filtered. The maps cover about 2000 square degrees in the sky, with a resolution of $\sim$ 10 arcmin. Maps have been obtained from the time-ordered data in several ways, ranging from simple naive pixelization all the way to maximum likelihood map making (see Borrill (1999), Hivon et al. (2002), Natoli et al. (2001) for the different methods). All methods produce consistent results. These maps contain very faint features (down to 10ppm of the absolute sky brightness). We tested the accuracy of the maps by comparing independent channels at the same frequency. We created two channels with similar noise performance by comparing bolometer B150A and the average of B150A1 and B150A2. The sum and difference maps are shown in fig.1. It is evident that most of the signal, even at high galactic latitudes, comes from the sky, while system noise is subdominant. A test for systematic effects was done in a similar way, by comparing the maps obtained at two different scan speeds during the flight. We scanned the sky at 1 degree per second for the second half of the flight, and at 2 dps in the first half. At 2 dps the sky signal is converted into an electrical signal at twice the frequency than it was at 1 dps, while instrument related effects (transfer function, 1/f noise, microphonic lines, etc.) remain at the same frequency. For the each detector we compare the map from data taken at 1 dps to the map from data taken at 2 dps. The difference map should contain only systematic effects, which are evidently much dimmer than the signals in the sum map (see fig.2). The simultaneous detection of 4 frequencies provided by the instrument is the main tool we have to investigate the origin of the detected structures. When the maps at the 4 different frequencies are plotted in CMB thermodynamic temperature units (μK), structures in the maps with the spectrum of the CMB will appear the same at all frequencies. This

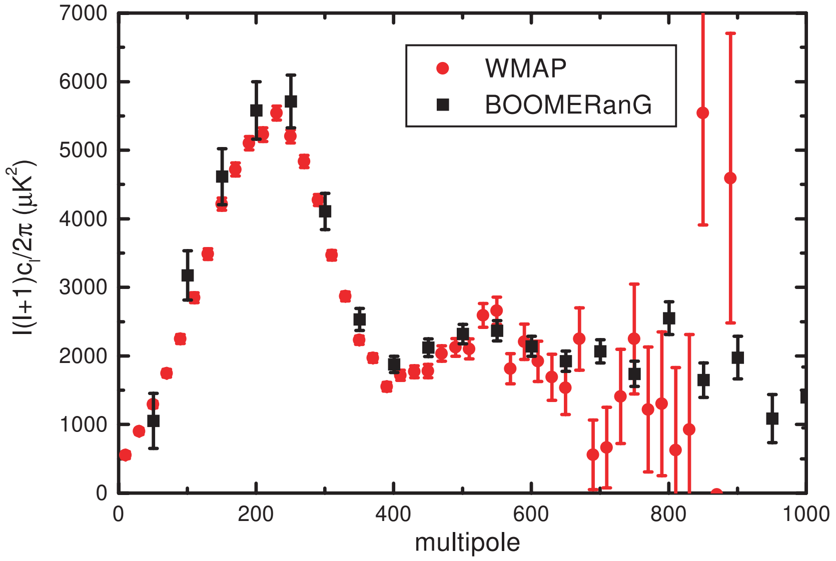

Fig. 3. Angular Power spectrum of the CMB measured by BOOMERanG (squares) in its 1998 flight. The circles are the recent measurements by the WMAP satellite.

test shows that most of the structure visible in the maps is indeed due to CMB anisotropies (de Bernardis et al. (2000)). The signal to noise ratio is high at 90, 150, 240 GHz. The interstellar dust monitor channel at 410 GHz shows no evidence for CMB and very little dust emission at high latitudes. Independent evidence for the cosmological origin of the structures comes from the study of the gaussianity of the signals in the maps. Gaussianity of the temperature fluctuations is evident even plotting the histogram of the temperature fluctuations in the high latitude section of the 150 GHz map . This is a non-trivial result. As a matter of facts maps of the sky with the same resolution at higher and lower frequencies, where the sky is not dominated by the CMB, are not gaussian at all. BOOMERanG data at 150 GHz at lower galactic latitudes and at 410 GHz at all latitudes do not have gaussian pixel histograms. Minkowski functional analysis (characteristics of the shapes of the hot and cold spots) also shows that the high latitude part of the 150 GHz map is gaussian: any non-gaussian components should account for less than a few percent of the fluctuations present in the 150 GHz map (Polenta et al. (2002)). Gaussianity of the CMB temperature fluctuations is one of the key prediction of the standard cosmological paradigm, and these data are fully consistent with the prediction.

4. The angular power spectrum of the CMB

If the fluctuations are random and gaussian distributed, all the information contained in the maps is provided by the angular power spectrum. The power spectrum has been estimated from the maps using different algorithms, all producing consistent results (de Bernardis et al. (2000), Netterfield et al. (2002), Ruhl et al. (2003)). The multipoles range where BOOMERanG is sensitive is limited on one side by the presence of 1/f noise, which limits the sensitivity of the instrument at $\ell \lesssim 20$; on the other side by the beam size (of the order of 10 arcmin) and by the precision of its measurement: this limits the sensitivity at $\ell \gtrsim 1000$. In fig.3 we present the latest version of the power spectrum, obtained from 4 channels and about 2% of the sky. Three peaks are detected (de Bernardis et al. (2002), Ruhl et al. (2003)), at multipoles $216, 536, 825$, thus providing evidence for the presence of acoustic oscillations of the photons-baryons fluid in the primeval fireball. Moreover, the location of the first peak measures the size of the acoustic horizon at recombination, thus providing a sensitive angular size - distance test. From this, the density parameter Ω is measured to be very close to 1 ($\Omega = 1.03 \pm 0.05$). The other parameters affecting the shape of the power spectrum are the physical density of baryons $\Omega_b h^2$ and the spectral index n_s of the power spectrum of primordial density $P(k) = Ak_s^n$. Increasing the first parameter the second peak is depressed with respect to the first one, while the third peak is enhanced; increasing n_s, instead, both the second and third peaks are enhanced. Being able to extend our measurement all the way to $\ell \sim 1000$ we break the degeneracy between the two parameters, and constrain both quite efficiently: $\Omega_b h^2 = 0.023 \pm 0.003$; $n_s = 1.02 \pm 0.08$. The agreement with the baryon density required by Big Bang nucleosynthesis is very good. Also, $n_s \sim 1$ is a generic prediction of all Inflation models. In fig.3 we also report the recent measurement of the angular power spectrum of the CMB from the NASA-WMAP satellite (Bennett et al. (2003)). Despite of the completely different techniques (balloon vs. deep space, bolometers vs coherent detectors, 150 GHz vs 20-90 GHz, sky patch vs full sky, different foregrounds, different calibration methods, systematics etc.) the agreement of the two results is stunning. WMAP makes a better job at multipoles $\lesssim 600$ because of the full sky coverage (the results are limited by cosmic variance up to $\ell \lesssim 350$); at higher multipoles BOOMERanG has more sensitivity due to the narrower beam, and can constrain the third peak, which is not visible in the WMAP spectrum. This compensates in part the poor gain calibration of BOOMERanG (10 % for BOOMERanG vs $\lesssim$ 1% for WMAP), so that the accuracy of the determination for most of the cosmological parameters improves only by a factor of a few in WMAP.

5. Interstellar emission in the BOOMERanG 1998 maps

Boomerang maps are not only CMB. We have obtained useful maps of the interstellar dust (ISD) brightness. The 410 GHz channel is a very good dust monitor. It samples dust emission at a frequency much closer to the CMB than the IRAS and DIRBE surveys (at 3000 and 1250 GHz respectively). We also detect dust emission at 90, 150, and 240 GHz (Masi et al. (2001)). The interstellar component of the BOOMERanG maps has been found by correlating (Masi et al. (2002)) the maps with a dust template obtained from the IRAS/DIRBE maps (Schlegel et al., (1999), Finkbeiner et al., (1999)). The advantage of correlating with IRAS is that the noises in the two experiments are uncorrelated, and the CMB contribution is completely negligible in the IRAS data, which are dominated by ISD. Any instrumental correlation internal to B98 does not contribute to the regression, so any detected correlation must be due to interstellar dust. We find very significant correlations at 410, 240 and 150 GHz even at high galactic latitudes, while the correlation is marginal at 90 GHz and high latitudes. Once the maps are converted in brightness units, the best fit slopes of the regression BOOMERanG vs IRAS give the spectrum of dust bright-

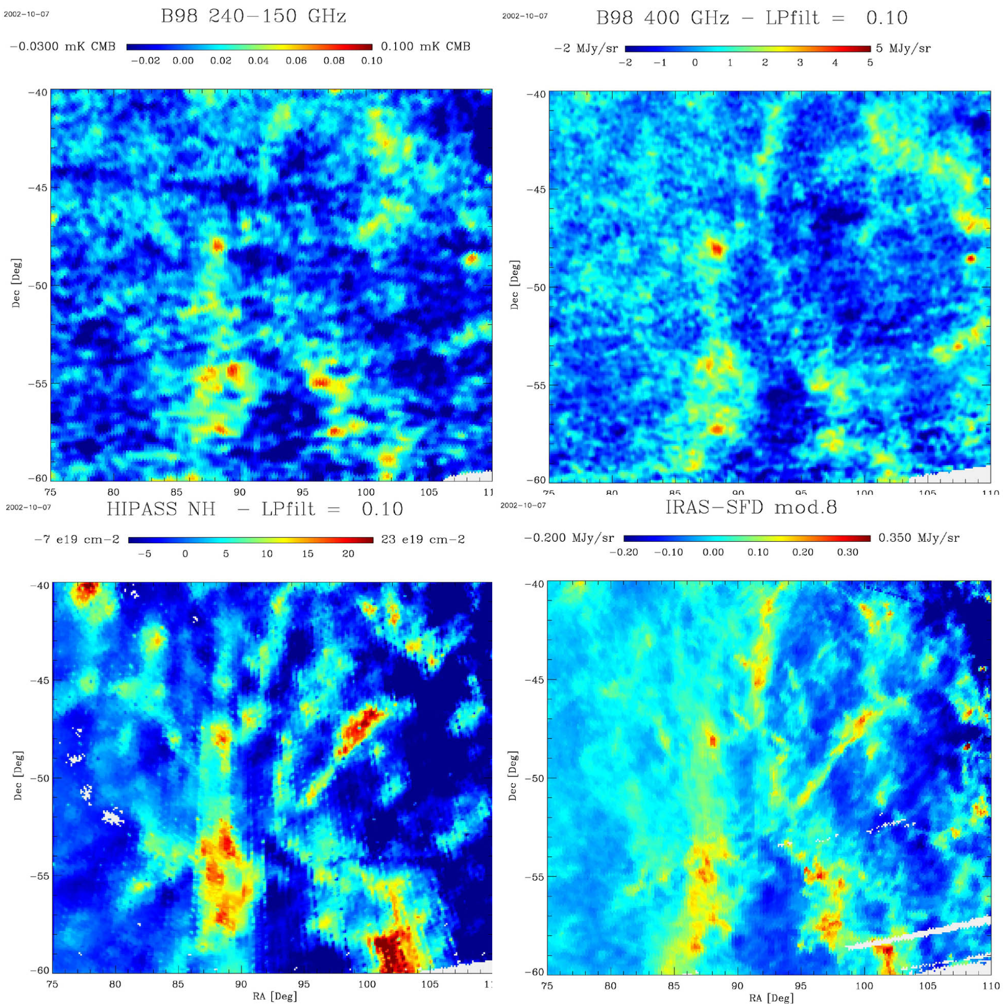

Fig. 4. Interstellar dust emission detected by BOOMERanG at $\sim$ 240 GHz (top left) and at $\sim$ 410 GHz (top right), and by IRAS at 3000 GHz (bottom right). The hyperfine transition of neutral hydrogen at 21 cm is reported, for comparison, in the lower left panel (from the HIPASS survey). The lower maps have been filtered to mimic BOOMERanG response to diffuse emission. As a consequence all angular scales larger than $\sim 10^o$ have been removed.

ness fluctuations. This is consistent with a single temperature Rayleigh-Jeans thermal spectrum, times an emissivity $\epsilon = \epsilon_0 \nu^\gamma$. We find $\gamma = (1.2 \pm 0.3)$ at low latitudes, and $\gamma = (2.3 \pm 1.0)$ at high latitudes. This can be used to estimate the level of Galactic contamination in the 150 GHz maps. It turns out that the power spectrum of the interstellar dust component is less than 1% of the power spectrum of the CMB at 150 GHz (Masi et al. (2001)). The morphology of dust clouds in the BOOMERanG map can be studied at 410 GHz and by taking the difference between the 240 GHz and the

150 GHz channels (in CMB units, so that any CMB is removed and only sources with non-CMB spectra contribute to the resulting map). In fig.4 we compare the morphology of the two CMB-free BOOMERanG maps to the morphology of two independent indicators of ISD: the 100 μm emission sampled by IRAS/DIRBE and the 21 cm hyperfine transition of H sampled in the HIPASS survey. The agreement is remarkable.

6. B2K: the polarization sensitive BOOMERanG

The CMB is expected to be slightly polarized, due to the anisotropy in the incoming radiation seen by the electrons scattering the photons for the last time. There are three processes producing this effect. The first one (scalar component, o E-modes) is the presence of velocity gradients (converging or diverging flux) in the matter-radiation fluid at recombination. In the rest-frame of the scattering electron, these velocity gradients produce quadrupole anisotropy in the incoming radiation through the Doppler effect, and thus linear polarization in the scattered photons. Since the quadrupole is small, the expected polarization is also small, at a level of $\lesssim$ 10% of the anisotropy. Overdensities oscillate acoustically before recombination: the velocity is minimum for maximum density contrast, while is maximum for minimum density contrast. For this reason the power spectrum of the scalar component of the CMB polarization has its maxima at multipoles where the temperature power spectrum has its dips, and has its minima where the temperature spectrum has its peaks. Gravity waves (tensor modes) produced in the inflation also produce anisotropy in the incoming radiation, generating E-modes but also a rotational component, the so-called B-modes of the polarization pattern. The B-modes represent a window on the very early universe, their level being sensitive to the energy scale of Inflation. However, the level of B-modes in the CMB polarization is much smaller than the level of E-modes. Only high accuracy measurements will be able to detect their signature. Finally CMB photons are re-scattered at redshift $\gtrsim 6$, when the first stars re-ionize the universe: this also produces polarization at the largest scales. From what I just said, it is evident that there are many reasons to investigate CMB polarization experimentally. CMB polarization (E-modes) has been detected by the DASI esperiment (Kovac et al. (2002)). However, the precision of this detection is not enough to constrain models. The correlation between anisotropy and polarization has been detected by the WMAP satellite (Kogut et al. (2003)). Here the $< TE >$ power spectrum is perfectly consistent with what is expected from the anisotropy power spectrum $< TT >$, providing a wonderful confirmation of the paradigm. Also, at large angular scales a signature of reionization is evident in the $< TE >$ spectrum at low multipoles, locating the formation of first stars at $10 \lesssim z_R \lesssim 20$.

The BOOMERanG payload has been recovered after the 1998 flight and modified implementing a polarization sensitive focal plane. This includes four polarization sensitive bolometers (PSB) at 150 GHz, with a resolution of 9 arcmin, and four 2-channel photometers (245/345 GHz) with resolution 6.5 arcmin. The sensors are arranged in two rows along the azimuth (scan) direction, offset by 0.5^o in elevation. The distance between pixels is 0.5^o. The experiment has been flown on Jan.6, 2003, and remained at altitude higher than 90kft for 11.6 days. During the flight we scanned three regions. We made a deep survey at high galactic latitudes ($\sim$ 100 square degrees, with a typical integration time of 60s per 7 arcmin pixel) targeting at the measurement of the $< EE >$ power spectrum of polarization. We also made a shallow survey of about 1100 square degrees, at galactic latitudes ranging from -30^o to -60^o. The targets of this survey are the measurements of the power spectra of $< TE >$ and

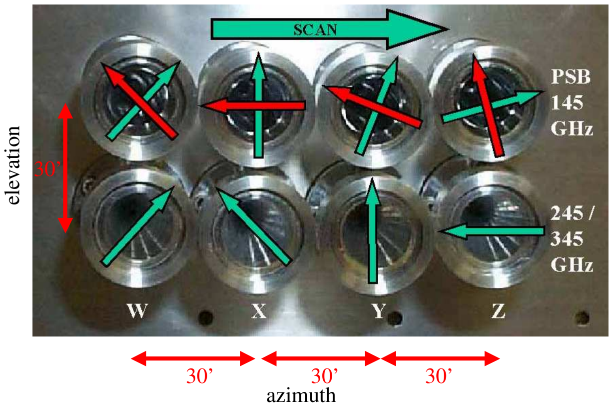

Fig. 5. Focal plane of the 2003 BOOMERanG-B2K focal plane. The polarization directions sensed by the detectors are indicated by the arrows. The scan is along the azimuth direction.

$< TT >$. Finally we scanned a region about 400 square degrees wide across the Galactic plane, to study the polarization of interstellar dust. The data analysis is currently underway, and the quality of the dataset looks gorgeous.

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