

EXPERIMENTAL COSMIC MICROWAVE BACKGROUND RESEARCH

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Plan of the talk:

- What is the CMB
- Which are the observables
- Experimental problems:
 - Atmospheric and Instrument Emission
 - Detector sensitivity
 - Foregrounds
 - Systematics
- Thermal Detectors (Coherent detectors)
- Current results for CMB anisotropy
- Measurements of CMB polarization
- **Future** directions:
 - High angular resolution SZ
 - High frequency SZ
 - CMB polarization B-modes



What is the CMB



According to modern cosmology:



An abundant background of photons filling the Universe.

- **Generated** in the very early universe, less than 4 μ s after the Big Bang (10⁹ γ for each baryon)
- Thermalized in the primeval fireball (in the first 380000 years after the big bang) by repeated scattering against free electrons
- **Redshifted** to microwave frequencies **and diluted** in the subsequent 14 Gyrs of expansion of the Universe



toda

Why is the CMB important

- Is the most ancient fossil remnant of the early Universe.
- Its characteristics tell us a lot about the physical processes happening in the early Universe.
- Modern cosmology is heavily based on observations of the CMB.

Primeval fireball

CMB photons

CMB and cosmology

- 1992: COBE-FIRAS measures the spectrum of the CMB with incredible precision (1/10000)
- The thermal spectrum at 2.735K and the high photons to barions ratio together with the measured primordial abundances of light elements is evidence for a hot initial phase of the Universe.

J. Mather et al. 1992







CMB observables

- The CMB is ONLY slightly anisotropic.
- The brightness ۲ (temperature) fluctuations are due to small density fluctuations present in the primeval fireball, and to their motions:

 $\frac{\Delta T}{T} = \frac{1}{4} \frac{\Delta \rho_{\gamma}}{\rho_{\gamma}} + \frac{1}{3} \frac{\Delta \varphi}{c^2}$

Photon

Density

fluctuations

 $1 \Delta \varphi$

Gravitational

redshift





Which is the power spectrum?

- The angular power spectrum of the CMB depends on the physical processes happening in the early universe, during the primeval fireball phase.
- The primeval fireball is an expanding plasma, slowly decreasing its temperature, where photons and matter are in thermal equilibrium
- There are 10⁹ photons for each baryon, so photon pressure is very important.
- For T > 0.8 eV the energy density of photons dominates, while at later times the energy density of matter dominates.
- At T = 0.26 eV the plasma neutralizes, H atoms are formed, and the universe becomes transparent to photons (recombination). We see the image of the CMB as it was there, when photons were last scattered.





The BOOMERanG map of the last scattering surface

adented @ • How is the structure we expe see in the primeval plasma at recombination? • It depends on -the physics of the primeval fireball -the physics of the very early Universe

-the geometry of space



The BOOMERanG map of the last scattering surface



Physics of the primeval fireball



After recombination, density perturbation can **grow** and create the hierarchy of structures we see in the nearby Universe.





Geometry of the Universe (curvature)







Physics of the very early Universe (Inflation)



The angular power spectrum depends the cosmological parameters

Dependance on Ω (curvature drives the location of first peak).

Not as simple as in these examples (see S.Weinberg, astro-ph/0006276)

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Q.L





CMB observables

 The angular power spectrum c_l of the anisotropy defines the contribution to the rms from the different multipoles:

$$\Delta T(\theta, \varphi) = \sum_{\ell, m} a_{\ell m} Y_{\ell}^{m}(\theta, \varphi)$$
$$c_{\ell} = \langle a_{\ell m}^{2} \rangle$$

$$\left\langle \Delta T^{2} \right\rangle = \frac{1}{4\pi} \sum_{\ell} (2\ell + 1)c_{\ell}$$

- A real experiment will not be sensitive to all the multipoles of the CMB.
- The window function w_l defines the sensitivity of the instrument to different multipoles.
- The detected signal will be:

$$\left\langle \Delta T^2 \right\rangle_{meas} = \frac{1}{4\pi} \sum_{\ell} (2\ell + 1) w_{\ell} c_{\ell}$$

 For example, if the angular resolution is a gaussian beam with s.d. σ, the corresponding window function is

$$w_{\ell}^{LP} = e^{-\ell(\ell+1)\sigma^2}$$



0.0

multipole

$$w_{\ell}^{LP} = e^{-\ell(\ell+1)\sigma^2}$$







The polarization of the CMB

- CMB photons are last scattered by electrons at recombination
- It's a *Thomson scattering*
- The cross-section depends on the scattering angle

$$I' = \frac{3\sigma_T}{16\pi}I(1+\cos^2(\theta))$$





- The scattered radiation can get some degree of linear polarization in the scattering, even if the incoming radiation is not polarized.
- In terms of the Stokes parameters:

$$I' = \frac{3\sigma_T}{16\pi} I(1 + \cos^2(\theta))$$
$$Q' = \frac{3\sigma_T}{16\pi} I \sin^2(\theta)$$
$$U' = 0$$
$$V' = 0$$

$$\vec{E}(t) = E_x \cos(\omega t - \theta_x)\hat{x} + E_y \cos(\omega t - \theta_y)\hat{y}$$

$$\begin{cases}
I = \left\langle E_x^2 \right\rangle + \left\langle E_y^2 \right\rangle \\
Q = \left\langle E_x^2 \right\rangle - \left\langle E_y^2 \right\rangle \\
U = \left\langle 2E_x E_y \cos(\theta_x - \theta_y) \right\rangle = \left\langle E_{x'}^2 \right\rangle - \left\langle E_{y'}^2 \right\rangle \\
V = \left\langle 2E_x E_y \sin(\theta_x - \theta_y) \right\rangle
\end{cases}$$



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Q' is non-zero, i.e. the scattered radiation is polarized, if the incoming radiation I(θ,φ) has a Quadrupole distribution

• If the local distribution of incoming radiation in the rest frame of the electron has a *quadrupole moment*, the scattered radiation acquires some degree of linear polarization.



- Before recombination there is no quadrupole component in the radiation: it arrives at recombination unpolarized.
- During recombination, **Gradients** in the velocity field can produce a quadrupole in the framework of the scattering electron.



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• During recombination, **Gradients** in the velocity field can produce a quadrupole in the framework of the scattering electron.



- Before recombination there is no quadrupole component in the radiation: it arrives at recombination unpolarized.
- During recombination, **Gradients** in the velocity field can produce a quadrupole in the framework of the scattering electron.



• This component of the CMB polarization field is called **E** component, or **gradient component**. This is the only kind of polarization produced at recombination by scalar perturbations.



- It is related to velocity fields. For **acoustic oscillations**, it will be maximum for perturbations with maximum velocity and zero density contrast.
- So we expect **peaks in this polarization** power spectrum where we have **minima in the temperature** power spectrum.
- The amplitude of the polarization signal depends on the **length of the recombination process** (it is not produced before, nor later).

- **Tensor perturbations (gravity waves)** also produce quadrupole anisotropy. The generation of a faint stochastic background of gravity waves is a generic feature of all **inflationary processes**.
- The resulting polarization pattern is shear-like.
- The amplitude of the effect is very small.
- This component of the CMB polarization field is called **B** component, or **curl component**.



- Velocity fields cannot produce B modes.
- Weak lensing can, but is subdominant at scales larger than 1 deg.
- Mathematical algoritms exist to separate B modes and E modes.
• The description in terms of Q and U is not invariant under rotation of the coordinate system:

$$Q' = Q\cos 2\theta + U\sin 2\theta$$
$$U' = -Q\sin 2\theta + U\cos 2\theta$$

- The description in terms of E and B is rotationally invariant.
- Velocity fields (scalar perturbations) produce E modes only.
- Inflation (tensor perturabtions) produces both E-modes and B-modes
- Four independent power spectra can be measured (the other combinations are 0 by symmetry):

$$c_{\ell}^{TT}, c_{\ell}^{TE}, c_{\ell}^{EE}, c_{\ell}^{BB}$$



Expected Patterns of Polarization in the Sky





From the BICEP website (Caltech)

- Finally, CMB is partially rescattered when the formazion of the first stars **re-ionizes** the universe (z>6).
- Since these additional scatterings happen much closer to us, they enhance polarization spectra only at large angular scales (I of the order of 20, corresponding to the size of the horizon at the epoch of reionization)





Why do we care about the polarization of the CMB?



- We can give an independent confirmation of the model
- We can detect isocurvature fluctuations mixed to the dominant adiabatic ones.
- We can test the velocity field present at recombination
 - We can detect the reionization happening when the first structures form
 - We can detect the signature of inflation in the B-modes pattern of polarization





Experimental Approach



CMB observables

- The spectrum peaks at 150 GHz
- The anisotropy, polarization and noise peak at 210-220 GHz
- These frequencies are high for coherent detectors, and low for thermal detectors.





Detectors

Detectors

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- Coerent detectors measure amplitude and phase of the em wave
- Thermal detectors measure the energy of the em wave
- On both sides, CMB research drove the development of new devices:
 - Cryogenic, ultra-low noise HEMT amplifiers (coherent)
 - Cryogenic "Spider Web" and "Polarization Sensitive" Bolometers (thermal)
 - Low sidelobe corrugated antennas
- Also, the two worlds are progressively mixed: for example waveguides and striplines are now used with cryogenic bolometers

Cryogenic Bolometers

adented @ The CMB spectrum is continuum and bolometers are wide band ulletdetectors. That's why they are so sensitive.



Fundamental noise sources are Johnson noise in the thermistor ٠ $(\langle \Delta V^2 \rangle = 4 k T R)$, temperature fluctuations in the thermistor $((<\Delta W^2> = 4kGT^2)$, background radiation noise $(T_{bkg}^{5}) \rightarrow$ need to reduce the temperature of the detector and the radiative background.

Cryogenic Bolometers

• In steady conditions the temperature rise of the sensor is due to the background radiative power absorbed *Q* and to the electrical bias power *P*:

 $G(T - T_0) = Q + P$

• The effect of the background power is thus equivalent to an increase of the reference temperature: $\begin{tabular}{l} T_0 \\ T_0 \end{tabular}$

$$P = G \left[T - (T_0 + \frac{Q}{G}) \right] = G(T - T_0') \quad \begin{array}{l} 0.28 \text{K} \\ 0.27 \text{K} \\ 0.27 \text{K} \\ 0.26 \text{K} \end{array}$$



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- A large α is important for high responsivity.
- Ge thermistors: $\alpha \approx 10 K^{-1}$
- Superconducting transition thermistors: $\alpha \approx 1000 K^{-1}$







•The absorber is micro machined as a web of metallized Si_3N_4 wires, 2 µm thick, with 0.1 mm pitch.

•This is a good absorber for mm-wave photons and features a very low cross section for cosmic rays. Also, the heat capacity is reduced by a large factor with respect to the solid absorber.

•NEP ~ 2 10^{-17} W/Hz^{0.5} is achieved @0.3K •150µK_{CMB} in 1 s

•Mauskopf *et al*. Appl.Opt. **36**, 765-771, (1997)



$ \frac{\nu_0}{(\text{GHz})} $	au (ms)	η_{opt}	G (pW K ⁻¹)	${ m R}$ (M Ω)	NEP (1 Hz) $(10^{-17} \text{ W}/\sqrt{\text{Hz}})$	$\frac{\text{NET}_{CMB}}{(\mu \text{K}\sqrt{\text{s}})}$
90	22	0.30	82	5.5	3.2	140
$150 \mathrm{sm}$	12.1	0.16	85	5.9	4.2	140
150mm	15.7	0.10	88	5.5	4.0	190
240	8.9	0.07	190	5.7	5.7	210
410	5.7	0.07	445	5.4	12.1	2700

Table 5. In-flight bolometer performance

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Note. — In-flight bolometer performance. The 150 GHz channels are divided into single mode (150sm) and multimode(150mm). The optical efficiency of the channels decreased significantly from the measured efficiency of each feed structure due to truncation by the Lyot stop. The NEP is that measured in flight, and includes contributions from detector noise, amplifier noise, and photon shot noise.

Crill et al., 2003 – BOOMERanG 1998 bolometers

Cryogenic Bolometers

- Ge thermistor bolometers have been used in many CMB experiments:
 - COBE-FIRAS, ARGO, MAX, BOOMERanG, MAXIMA, ARCHEOPS
- Ge thermistor bolometers are extremely sensitive, but slow: the typical time constant C/G is of the order of 10 ms @ 300mK
- Transition Edge Superconductor (TES) thermistors can do much better using electro-thermal feedback (100 μs) – Recent development (hear Adrian Lee, next talk)







Bolometer Arrays

- Once bolometers reach BLIP conditions (CMB BLIP), the mapping speed can only be increased by creating large bolometer arrays.
- BOLOCAM and MAMBO are examples of large arrays with hybrid components (Si wafer + Ge sensors)
- Techniques to build fully litographed arrays for the CMB are being developed.
- TES offer the natural sensors. Hear A. Lee, D. Benford, A. Golding ..



Bolocam Wafer (CSO)



MAMBO (MPIfR for IRAM)

Mapping speed



- Mapping speed will be enormously increased by the use of arrays of bolometers.
- These are being developed in several labs
- See e.g.
 - Holland et al. MNRAS 303, 659, (1999)
 - Kreysa et al. SPIE **3357**, 319, (1998)
 - Glenn et al. SPIE **3357**, 326, (1998)
 - Turner et al., Appl. Opt., **40**, 4291, (2001)
 - Griffith et al., ESA-SP460, 37, (2001)
 - Lamarre et al., Astroph. Lett. & Comm, **37**, 161, (2000)
 - Dowell et al., proc. AAS **198**, 05.09 (2001)
 - And the papers presented here.

Coherent Detectors



- Very low noise HEMT amplifiers, cooled at 20K have been developed (NRAO).
- They have been used in many CMB experiments: TOCO, DASI, CBI, WMAP and are the baseline for Planck-LFI.
- Hear the talk from L.Terenzi



Atmosphere

CMB observables

- The spectrum peaks at 150 GHz
- The earth atmosphere is emissive (and not very transparent) in the same range.
- Sensitive observations must be carried out above the earth atmosphere: space carriers are required.



- The average emission of the atmosphere, of the instrument, and of the CMB, can be rejected using modulation techniques.
- While average brightness measurements of the CMB definitely require spaceborne measurements, anisotropy measurements can be carried out at lower altitudes, in selected atmospheric windows.
- Also, atmospheric emission is basically unpolarized.



and the and a How to do this 0 ß Party. Atmospheric transmission at different altitudes 2ta-10.gein • Frequency (GHz) 2000 800 600 400 1000 1 0.8 40 km0.6 0.4 0.2 0 1 Transmission 0.8 35 km 0.6 0.4 0.2 $\frac{0}{1}$ 0.8 12.5 km (SOFIA)-0.6 0.4 0.20 100 200 400 600 B00 1000 Wavelength (μm)

Atmospheric emission and noise

- Even an in-band • transmission of 95% results in a 40 km 35 km 15K background, loading the 0.95 detectors, and with significant fluctuations, 0.9 increasing detector noise
 - Going to 40Km of altitude, atmospheric emissivity drops algnificantly.



 Assuming ideal W/Hz^{0.5}) bolometers, matched to the atmospheric background, the E convivalent E NEP (power degrades with atmospheric background for two reasons: optical loading and photon noise.





BALLOON BORNE OBSERVATIONS CAN BE 4-10 TIMES MORE SENSITIVE THAN AIRBORNE ONES (assuming same integration time, $\lambda/\Delta\lambda$ =10, only photon noise, no turbulence)



Modulation Techniques

Scanning telescopes

- The beam scans the sky at constant speed v (°/s) •
- Different multipoles in the CMB temperature field produce ۲ different sub-audio frequencies in the detector (see e.g. astroph/9710349)

 $\Gamma(f)$ $l(l+1) c_{l}$ $f = \mathbf{v} \mathbf{I}/\pi$ Examples:

-v=1 o/s, I=200 -> f=1.1 Hz

۲

- v = 1 o/s, I = 1000 - f = 5.5 Hz

This technique allows to produce wide sky maps, so that a wide ٠ multipoles coverage of the power spectrum can be obtained in a single experiment.









The sky scan

- The image of the sky is obtained by slowly scanning in azimuth (±30°) at constant elevation
- The optimal scan speed is between 1 and 2 deg/s in azimuth





- The scan center constantly tracks the azimuth of the lowest foreground region
- Every day we obtain a fully crosslinked map.


Map of 6% of the sky

Spinning during a polar night flight, ARCHEOPS has covered. 25% of the sky, and mapped the CMB over 13% of the sky



A. Benoit, et al. A&A 2003





Foregrounds



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From the WMAP web site. In reality at 150 GHz the dust anisotropy is << of the CMB anisotropy in most of the sky







Current results

75

80

85

2000: BOOMERanG and MAXIMA map the temperature fluctuations of the CMB at sub-horizon scales (<1⁰).

• The signal is well above the noise and has the correct frequency spectrum.



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100

RA [Deg] BOOMERanG 150 GHz

2000: BOOMERanG and MAXIMA map the temperature fluctuations of the CMB at sub-horizon scales ($<1^{\circ}$).

The signal is \bullet well above the noise and has the correct frequency spectrum.



2000: BOOMERanG and MAXIMA map the temperature fluctuations of the CMB at sub-horizon scales ($<1^{\circ}$).

• The signal is well above the noise and has the correct frequency spectrum.



aresented

- The power spectrum of the CMB anisotropy features a distinctive peak at multipole 210 and overtones at multipoles 540 and 830.
- There are acoustic oscillations in the primeval plasma



June 2002

autented





The peak at multipole 210 means that typical size of the anisotropies is 1°, which means that the geometry of the universe is flat (Ω=1, as predicted by inflation)



• The amplitudes of the first, second and thin peaks allows to estimate $\Omega_b=0.02$, in agreement with BBN.



• The slope of the power spectrum of the CMB anisotropy agrees with the expectations of the basic inflationary model (n=1).

P. de Bernardis et al., Nature, 404, 955-959, 2000
S. Hanany et al., Ap.J., 545, L5-L9, 2000
A. Lange et al., PRD 63, 042001, 2001
R. Stompor et al., Ap.J., 561, L7, 2001
A. Lee et al., Ap.J., 561, L1, 2001,
B. Netterfield et al. Ap.J. 571, 604, 2002
P. de Bernardis et al. Ap.J. 564, 559, 2002
N. Halverson et al., Ap.J., Astro-ph/0104488-89-90, 2002
A. Benoit et al., A&A, 399, L19 and L25, 2003
J. Ruhl et al. Ap.J submitted astro-ph/0212229, 2003

- CMB and cosm It is shown that Galactic ightarrowcontamination at 150 GHz is less than 1% of the CMB fluctuations PS at multipole 200. This confirms that precision cosmological observations will be possible from satellite experiments in a wide area of the sky. S. Masi et al. Ap.J. 553, L93, 2001
- The image of the CMB is shown to be accurately gaussian as predicted by inflation. G. Polenta et al. Ap.J. **572**, L27, 2002; G. De Troia et al. MNRAS in press





CBI: Cosmic Background Imager

- Same technology as DASI (larger telescopes)
- Operation from Atacama desert (5000 m o.s.l.)
- I-space resolution still coarse
- New data :

astro-ph/0205384,5,6,78

- Very good consistency with other experiments at I < 1000.
- New data up to l = 3500.
- Detected fluctuations with the same mass of clusters of galaxies.
- The damping tail is evident !
- Excess at I=2500.
- Only one frequency (30 GHz).



- 2002: The Degree Angular Scale Interferometer (PI J. Carlstrom)) at the south pole has recently detected for the first time the linear polarization of the CMB
- astro-ph/0209478
- astro-ph/0209476
- at a level consistent with the concordance model.





- 2003: First results from WMAP, the CMB anisotropy mission of NASA, working from L2.
- A beautiful, firm confirmation of all we know about the CMB...
- and more:
 - Optical depth of reionization (from polarization)
 - Anisotropy low at large scales



- 2003: First results from WMAP, the CMB anisotropy mission of NASA, working from L2.
- The TT power spectrum, limited by cosmic variance up to =350
- The power spectrum of TE (correlation between anisotropy and polarization) in agreement with the acoustic oscillations scenario, and featuring an excess at low I.













Cosmological Parameters



Compare with same weak prior on 0.5<h<0.9

WMAP

(100% of the sky) Bennett et al. 2003

- $\Omega = 1.02 \pm 0.02$
- $n_s = 0.99 \pm 0.04 *$
- $\Omega_{\rm b}h^2 = 0.022 \pm 0.001$
- $\Omega_{\rm m}h^2 = 0.14 \pm 0.02$
- $T = 13.7 \pm 0.2 \text{ Gyr}$
- $\tau_{\rm rec} = 0.166 \pm 0.076$

BOOMERanG

(4% of the sky) astro-ph/0212229

- $\Omega = 1.03 \pm 0.05$
- $n_s = 1.02 \pm 0.07$
- $\Omega_{\rm b}h^2 = 0.023 \pm 0.003$
- $\Omega_{\rm m} h^2 = 0.14 \pm 0.04$
- $T=14.5\pm1.5$ Gyr

• The Future :



Polarization of the CMB High Resolution High Frequency



CMB polarization measurements

Linear Polarimeter

source

polarizer

θ



- Intensity detector • A polarimeter is a device able to detect polarized light and measure its polarization characteristics.
- The simplest polarimeter we can imagine is a linear polarimeter, which can be built with a rotating polarizer in front of an intensity detector.
- An intensity detector is represented by a Stokes vector D=(1,0,0,0). The power detected by the detector from an optical beam with Stokes vector S is simply $w=DS=S_{o}$ (here S=(I,Q,U,V))
- If we put a polarizer in front of the detector, the polarizer is called analyzer, and the power detected will be w(θ) = $DM_{P}(\theta)S$

Polarizer or Diattenuator

• It attenuates the orthogonal components of an optical beam unequally:

$$\begin{cases} E'_{x} = p_{x}E_{x} \\ E'_{y} = p_{y}E_{y} \end{cases}$$

• Using the definitions of S and S'

$$\begin{pmatrix} I' \\ Q' \\ U' \\ U' \\ V' \end{pmatrix} = \begin{pmatrix} E'_x E'^*_x + E'_y E'^*_y \\ E'_x E'^*_x - E'_y E'^*_y \\ E'_x E'^*_y + E'_y E'^*_x \\ i(E'_x E'^*_y - E'_y E'^*_x) \end{pmatrix} \qquad \qquad \begin{pmatrix} I \\ Q \\ U \\ U \\ V \end{pmatrix} = \begin{pmatrix} E_x E^*_x + E_y E^*_y \\ E_x E^*_x - E_y E^*_y \\ E_x E^*_y + E_y E^*_x \\ i(E_x E^*_y - E_y E^*_x) \end{pmatrix}$$

• And inserting the expressions for E' we get $\begin{pmatrix} I'\\ O' \end{pmatrix} = \begin{pmatrix} p_x^2 + p_y^2 & p_x^2 - p_y^2 & 0 & 0 \\ p_x^2 - p_y^2 & p_x^2 - p_y^2 & 0 & 0 \\ p_x^2 - p_y^2 & p_x^2 + p_y^2 & 0 & 0 \\ \end{pmatrix}$

$$\begin{bmatrix} Q\\U'\\V' \end{bmatrix} = \frac{1}{2} \begin{bmatrix} p_x^2 - p_y^2 & p_x^2 + p_y^2 & 0 & 0\\ 0 & 0 & 2p_x p_y & 0\\ 0 & 0 & 0 & 2p_x p_y \end{bmatrix} \begin{bmatrix} Q\\U\\V \end{bmatrix}$$



$$\begin{array}{l} \text{Rotated Polarizer} \\ M_{C}(0) = M_{P}(0) = \frac{1}{2} \begin{pmatrix} p_{x}^{2} + p_{y}^{2} & p_{x}^{2} - p_{y}^{2} & 0 & 0 \\ p_{x}^{2} - p_{y}^{2} & p_{x}^{2} + p_{y}^{2} & 0 & 0 \\ 0 & 0 & 2p_{x}p_{y} & 0 \\ 0 & 0 & 0 & 2p_{x}p_{y} \end{pmatrix} = \frac{1}{def} \begin{pmatrix} \Sigma & \Delta & 0 & 0 \\ \Delta & \Sigma & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{pmatrix} \\ \bullet \text{ so } \qquad M_{P}(\theta) = \frac{1}{2} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{2} & -s_{2} & 0 \\ 0 & s_{2} & c_{2} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \Sigma & \Delta & 0 & 0 \\ \Delta & \Sigma & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{2} & s_{2} & 0 \\ 0 & -s_{2} & c_{2} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \\ \bullet \text{ and } \end{array}$$

$$M_{P}(\theta) = \frac{1}{2} \begin{pmatrix} \Sigma & c_{2}\Delta & s_{2}\Delta & 0\\ c_{2}\Delta & c_{2}^{2}\Sigma + s_{2}^{2}X & s_{2}c_{2}(\Sigma - X) & 0\\ s_{2}\Delta & s_{2}c_{2}(\Sigma - X) & s_{2}^{2}\Sigma + c_{2}^{2}X & 0\\ 0 & 0 & 0 & X \end{pmatrix} \qquad \begin{cases} \Sigma = p_{x}^{2} + p_{y}^{2}\\ \Delta = p_{x}^{2} - p_{y}^{2}\\ X = 2 p_{x} p_{y}\\ s_{2} = \sin 2\theta\\ c_{2} = \cos 2\theta \end{cases}$$

$$\begin{array}{c} \text{Linear Polarimeter} \\ & & \text{Polarizer (analyzer)} \\ \theta & & \text{Intensity detector} \end{array}$$

$$w = DM_{p}(\theta)S = (1,0,0,0) \frac{1}{2} \begin{pmatrix} \Sigma & c_{2}\Delta & s_{2}\Delta & 0\\ c_{2}\Delta & c_{2}^{2}\Sigma + s_{2}^{2}X & s_{2}c_{2}(\Sigma - X) & 0\\ s_{2}\Delta & s_{2}c_{2}(\Sigma - X) & s_{2}^{2}\Sigma + c_{2}^{2}X & 0\\ 0 & 0 & 0 & X \end{pmatrix} \begin{pmatrix} I\\ Q\\ U\\ V \end{pmatrix} \Rightarrow$$

$$w = \frac{1}{2} \left(\Sigma I + Q \Delta \cos 2\theta + U \Delta \sin 2\theta \right)$$

This polarimeter is not sensitive to circular polarization (no V). It is sensitive to linear polarization (Q and U) and to unpolarized light (I). If the polarizer is ideal: $\Delta = 1$; $\Sigma = 1$; X = 0

 $\Delta = 1 \quad ; \quad \Sigma = 1 \quad ; \quad X = 0$ $w = \frac{1}{2} \left(I + Q \cos 2\theta + U \sin 2\theta \right)$

Linear Polarimeter

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- If we are interested to the linear polarized component only, we can rotate continuously the polarizer: $\theta = \omega t$ and look only for the AC signal at frequency 2ω .
- This allows to reject the unpolarized component, even if it is dominant, and to remove all the noise components at frequencies different than 2ω (synchronous demodulation).

source

$$W = \frac{1}{2} \left(\Sigma I + Q\Delta \cos 2\omega t + U\Delta \sin 2\omega t \right)$$

$$W(t) = Rw(t) + N(t) = \frac{1}{2} R \left[\Sigma I + \Delta \left(Q \cos 2\omega t + U \sin 2\omega t \right) \right] + N(t)$$

$$K(t) = Rw(t) + N(t) = \frac{1}{2} R \left[\Sigma I + \Delta \left(Q \cos 2\omega t + U \sin 2\omega t \right) \right] + N(t)$$

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How do we separate Q and U $V(t) = Rw(t) + N(t) = \frac{1}{2}R[\Sigma I + \Delta(Q \cos 2\omega t + U \sin 2\omega t)] + N(t)$

- Neglecting the stochastic effect of noise (we integrate enough that N becomes negligible) and of the constant term (which we remove with the AC decoupling) $V(t) = Rw(t) = \frac{1}{2}R[\Delta(Q\cos 2\omega t + U\sin 2\omega t)]$
- We measure V and we want to estimate Q and U. We can use two reference signals, out of phase by T/8 and synchronously demodulate with them:
How do we separate
$$S_1$$
 and S_2
 $X = \frac{1}{T} \int_{0}^{T} V(t) \sin 2\omega t dt = \frac{1}{2} \frac{R\Lambda}{T} \left[Q \int_{0}^{T} \cos 2\omega t \sin 2\omega t dt + U \int_{0}^{T} \sin 2\omega t \sin 2\omega t dt \right]$
 $Y = \frac{1}{T} \int_{0}^{T} V(t) \cos 2\omega t dt = \frac{1}{2} \frac{R\Lambda}{T} \left[Q \int_{0}^{T} \cos 2\omega t \cos 2\omega t dt + U \int_{0}^{T} \sin 2\omega t \cos 2\omega t dt \right]$

$$X = \begin{bmatrix} \frac{1}{8} R \Delta \end{bmatrix} U$$
$$Y = \begin{bmatrix} \frac{1}{8} R \Delta \end{bmatrix} Q$$

- So the double linear polarimeter is insensitive to I and it is easy to calibrate.
- Is this a troubleless instrument ? No !
- It is inefficient (factor 1/8 from modulation and demodulation)
- It can be microphonic.



Wire-GridHalf-Wave PlateK-MirrorDoppio-Rombo di FresnelAll these techniques suffer for the need of long integration time:One needs to point to the same sky pixel during many cycles ofthe analyzer. It is thus difficult to produce extended maps of theCMB polarization.

A two-bolometers polarimeter ?



We can map the two orthogonal components of the linear polarization with two separate bolometers, and combine the two signals to retreive the Stokes parameters Q and U.



The modulation is obtained by scanning the sky at constant rate, so that the polarization signals are detected at a frequency far from the 1/f knee of the noise and far from the effect of instrumental drifts (similar to the anisotropy measurements with B98)

 $f = v I/\pi$: with I=300-1000 and v=1°/s f = 1.7-5.5 Hz

Terminology

- Co-polar response of the polarimeter C: response of the polarimeter to incoming radiation 100% polarized along the principal axis of the polarimeter. It is the product of the detector responsivity times the integral of the Co-polar beam response. Units: V/W or V/K
- Cross-polar response of the polarimeter X: response of the polarimeter to incoming radiation 100% polarized and orthogonal to the principal axis of the polarimeter. It is the product of the detector responsivity times the integral of the cross-polar beam response. Units: V/W or V/K
- Polarization efficiency = 1 X/C



Frequency content of detected signal

- The detected signal is the sum of several contributions.
- First order approximation, for bolometer #1:



PSB: Polarization Sensitive Bolometers (JPL+Caltech)



- 150 GHz
- Two wire-grid-like absorbers with matched NTD thermistors
- Rotated 90°
- Very close each other (60 µm) inside the same groove of a corrugated circular feedhorn









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Polarization-sensitive bolometers JPL-Caltech

3 μm thick wire grids, Separated by 60 μm, in the same groove of a circular corrugated waveguide

Planck-HFI testbed



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Polarization Sensitive Bolometers













50:10



elevation





Receiver Specifications

Freq	Bandwidth	#Channels	Beam FWHM	Exp. NET _{CMB}
145 GHz	$46~\mathrm{GHz}$	8	9.5'	$160 \ \mu K \sqrt{s}$
245 GHz	$100 \mathrm{GHz}$	4	6.5'	$290 \ \mu K \sqrt{s}$
345 GHz	$100 \mathrm{GHz}$	4	7'	$660 \ \mu K \sqrt{s}$

Polarization Efficiency

 $S(\theta) = \gamma(1 - \beta \sin^2(\theta - \theta_0))$

β is the polarization efficiency

PSB's have an efficiency of 90-95% Photometer channels have an efficiency > 97%







Each Detector is sensitive to one linear polarization.

A pair of orthogonal detectors measures:

$$S_{x} = \gamma_{x} \{ (1 - \beta_{x}/2) I + (\beta_{x}/2) Q \}$$

$$S_{y} = \gamma_{y} \{ (1 - \beta_{y}/2) I - (\beta_{y}/2) Q \}$$

If $\gamma_x = \gamma_y$ and $\beta_x = \beta_y$, we have

I =
$$\frac{S_x + S_y}{2 \gamma (1 - \beta/2)}$$
 Q = $\frac{S_x - S_y}{\gamma \beta}$

Instrument Calibration



- Absolute Calibration with respect to CMB anisotropies
 - Primary method: cross-calibration with WMAP and B98
 - Secondary methods: CMB dipole and RCW 38
- Beams
 - Primary: Quasar in Deep Scan Region
 - Secondary: Pre-flight using tethered source 1 km from Telescope
- Polarization
 - No measured polarized astrophysical sources at our frequencies
 - Primary polarization calibration done with a polarized far-field simulator





Calibration

• We need 1% calibration.



- This can be done, in the lab by means of a special full beam calibrator {measures Σ, Δ (or C and X) and the principal axis direction for each bolometer}
- In flight, thanks to WMAP (which is calibrated to better than 1% !).
- If we correlate the two bolometers separately with the unpolarized WMAP maps, we can estimate the responsivity to better than 1%.



Channel	Pixel based	C(l) based
B150A	0.95 +/- 0.03	0.96 +/- 0.02
B150A1	0.91 +/- 0.03	0.92 +/- 0.03
B150A2	0.98 +/- 0.03	0.98 +/- 0.02
B150B2	0.95 +/- 0.03	0.95 +/- 0.02
Sum	0.95 +/-0.03	0.95 +/- 0.01







Collimated Polarized Source

Used to measure the polarization efficiency and the polarization angles of the full integrated telescope.



Pre-flight calibrations

- The calibration of a polarimeter at ground is more difficult than the usual photometer calibrations.
- In particular is very important to study the co and cross polarization response (beam and integral) of the polarimeter
- We have developed a polarized, sinemodulated source filling the beam of the instrument to carry out a through polarization characterization of all the detectors.
- There are two wire grid polarizers (P1 and P2), and a 77K blackbody source with a diaphragm in the focus of the 1.3 m off-axis paraboloid, producing a 10' beam.
- Rotating P2 at constant speed we modulate the signal (sine wave).
- Rotating P1 (in steps) we change the illuminator from co-polar to cross-polar (and all intermediate directions).



The Calibrator









•Additional Pointing Sensors with 16 bit abs. encoders

Tracking Star Camera



Pointed Sun Sensor









BOOMERanG landed near Dome Fuji (h=3700m) after 14 days of flight. The data have been recovered. The payload is still there.







Region	Size (sq deg)	Goal	Time per 7' pixel
Deep CMB	115	<ee></ee>	60 sec
Shallow CMB	1130	<te> and <tt></tt></te>	3.3 sec
Galactic Plane	390	Polarized Foregrounds	4.7 sec



Polarization Maps:



Quick-look data / single pair (of 4) of 143 GHz PSBs /raw data (no compensation for gain drifts!)/ coarse attitude solution

Noise ~ 3µK/20' pixel in 100 square degree "deep" region

Resolution $\sim 10'$

Polarized dust emission evident near galactic plane




Optimal maps obtained with IGLS, the Rome pipeline (Natoli et al. 2001)



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Optimal maps obtained with IGLS, the Rome pipeline (Natoli et al. 2001)



E. Hivon



E. Hivon



E. Hivon

Boomerang 2002: ~ 200 square degrees





ell bins (Δ ell = 75) < 10% correlated

Bill Jones



Bill Jones





LANCK

Looking back to the dawn of time Un regard vers l'aube du temps

http://sci.esa.int/planck







QMW



						sted @ (m
Center Frequency (GHz)	857	545	353	217	143	100
Center Wavelength (mm)	0.35	0.55	0.85	1.38	2.1	3.0
Operating T (K)	0.1	0.1	0.1	0.1	0.1	0.1
Fractional Bandwidth	0.33	0.33	0.33	0.33	0.33	0.33
Bandwidth (GHz)	286	182	118	72	48	33
Number of unpolarised bolometers	4	4	4	4	4	4
Number of polarised bolometers	0	0	8	8	8	0
FWHM (arcmin)	5	5	5	5.5	7.1	9.2
dT/T CMB Sensitivity microK/K	6600	17	15	3.8	2.4	2.2
dT/T CMB Sensitivity microK/KvHz	2900 0	61.7	54.4	13.8	12.2	14.4
dT/T Sensitivity (U&Q) polarised			109	27.6	24.4	

Planck HFI









High Resolution and High Frequency

APEX, SP, ALMA ...

evented **OLIMP** An arcmin-resolution survey of the sky at mm and sub-mm wavelengths PI: Silvia Masi (Dipartimento di Fisica, La Sapienza, Roma) Collaboration with IFAC-CNR, INGV, Univ. of Cardiff, CEA Saclay, Univ. of Santa Barbara (http://oberon.roma1.infn.it/olimpo)

2.6 m



CMB anisotropy

SZ clusters

Galaxies





Olimpo: list of Science Goa

- Sunyaev-Zeldovich effect
 - Measurement of $H_{\mbox{\scriptsize o}}$ from rich clusters
 - Cluster counts and detection of early clusters -> parameters (Λ)
- Distant Galaxies Far IR background
 - Anisotropy of the FIRB
 - Cosmic star formation history
- CMB anisotropy at high multipoles
 - The damping tail in the power spectrum
 - Complement interferometers at high frequency
- Cold dust in the ISM
 - Pre-stellar objects
 - Temperature of the Cirrus / Diffuse component

Olimpo: The Primary mirro

- Lo specchio primario (2.6m diametro) e' stato verificato nel laboratorio proponente.
- Si tratta dello specchio piu' grande mai lanciato su un pallone stratosferico.
- Viene fatto oscillare lentamente per realizzare la modulazione.



Ud-10.90"

Olimpo: The Payload







La navicella e' stata disegnata e verificata. E' in fase di realizzazione presso una piccola impresa nazionale

OLIMPASSY 16



sented @

ECCANC Via Gel Villaria 3A - Fai 980 =1 TIME-1 SEGV (AVG) PowerGraphics EFACET=1 AVRES=Hat DMX =2.146 ann =. 120x-05 SHO: =33.286 1208-05 2.698 7.39711.095 14.794 10.492 22.19 25.889 29.587 33.286

There is still a lot to learn from C photons, and new technologies a ready ...



