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Polarimetry of the Cosmic Microwave Background from the Antarctic Plateau

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Abstract: Detection of linear polarisation at a level of 1 ppm or less, associated to the anisotropy of the cosmic microwave background, will confirm the cosmological origin of the observed anisotropy and provide information on the thermal history of the universe between the recombination epoch and now. In particular, detection of polarisation can help in deciding if the evolution of the universe included a reionisation epoch. We present the Mk3 model of our correlation polarimeter, an improved version of a system which has already been used for observations of the region of sky around the South Celestial Pole from Antarctica (in 1994 at Terra Nova Bay and in 1998 at Dome C).

Keywords: instrumentation: polarimeters — cosmology: cosmic microwave background

1 Introduction

Observations carried out from ground and space have shown that to a very high degree of accuracy the cosmic microwave background (CMB), the relic of the Big Bang which produced the universe we live in, has a Planckian frequency spectrum, is isotropically distributed and unpolarised. These properties tell us (for a general discussion see for instance Partridge (1995) and references therein) of the universe at $z \simeq 1000$ when the interactions between matter and radiation ended almost suddenly and the CMB status was practically frozen. However this picture holds only at the very beginning of the history of the universe when the interaction rate of matter and radiation was so high that the universe expansion rate, compared to it, was negligible. But at $z < 10^6-10^7$ the thermalisation process of the energy injected by many kinds of phenomena may have been incomplete. We can therefore look for deviations from a Planck distribution of the CMB spectrum (spectral distortions), spatial anisotropies, and residual polarisation.

The measured amplitudes of all these effects or their upper limits are extremely small, showing that the evolution of the universe went on through a series of almost perfect states of equilibrium and that the search of the above features is a difficult task. But their discovery would be so rewarding and useful for probing the history of the universe well before galaxies formed that their search is pursued with determination and is one of the most powerful tools of present day cosmology. Only anisotropies have been detected so far. The hunt for spectral distortions and residual polarisation is still going on. Here we will concentrate on polarisation. Its detection would allow:

- 1) to confirm the cosmological nature of the CMB anisotropies discovered in the last decade. In fact as Martin Rees pointed out in 1968 (Rees 1968)

a by-product of the diffusion of the CMB by Thomson scattering on irregularities (anisotropies) of the matter distribution is a finite degree of linear polarisation $\Pi = (\Delta T/T)_{\text{pol}}$. Because the CMB anisotropies $(\Delta T/T)_{\text{anis}}$ track the matter anisotropies we can write

$$\left(\frac{\Delta T}{T}\right)_{\text{pol}} = \alpha \left(\frac{\Delta T}{T}\right)_{\text{anis}} \quad (1)$$

where $\alpha \leq 0.1$ is a coefficient of proportionality whose dependence on the anisotropy angular scale is shown in Figure 1.

- 2) to discover if the evolution of our universe included partial reionisation of the matter–radiation mixture at an epoch between the recombination era and the present era. In fact, at angular scales greater than

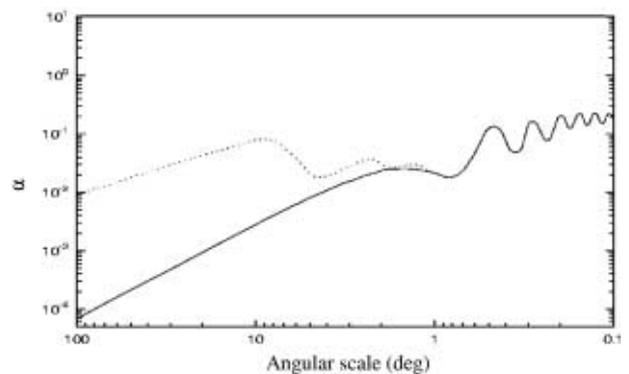


Figure 1 Trend of the ratio α between polarisation and anisotropy versus the angular scale θ in a standard Big Bang model with (dotted line) and without (continuous line) reionisation after recombination. The exact trend depends on the particular recipe of the parameters (H_0 , Ω_b , Ω_Λ , etc.) used to describe the Universe model (adapted from Melchiorri & Vittorio 1996).

Table 1. Measured upper limits to CMB polarisation

Reference	Wavelength (cm)	Angular scale ($\Delta\theta$)	Polarisation degree (Π)	Sky region
<i>Linear polarisation</i>				
Subrahmanyam et al. 2000	3.4	0.03°	$(5.7\text{--}6.2) \times 10^{-6}$	$\delta \simeq -50$
Wilson 1980	7.35	15°	$\leq 10^{-1}$	–
Partridge et al. 1988	6.0	18''–160''	$\leq (1.4\text{--}0.4) \times 10^{-4}$	$\delta = +80$
Nanos 1979	3.2	15°	$\leq 6 \times 10^{-4}$	$\delta = +40$
Torbet et al. 1999	1–0.75	2.9°, 2.1°, 1.6°, 1.2°, 0.9°	$\leq (1.4, 2.0, 1.0,$ $1.5, 2.9) \times 10^{-5}$	$\delta = +63$
Lubin & Smoot 1981	0.91	7°–15°	$\leq 6 \times 10^{-5}$	$-37 \leq \delta \leq +63$
Sironi et al. 1998b	0.91	7°–14°	$\leq 1 \times 10^{-4}$	SCP
Wollack et al. 1993	1.2–0.8	1.2°	$\leq 9 \times 10^{-6}$	NCP
Hedman et al. 2001	0.33	0.24°	$\leq 3.7 \times 10^{-5}$	$\delta = +89$
Caderni et al. 1978	0.05–0.3	1.5°–40°	$\leq (10\text{--}1) \times 10^{-4}$	GC, NGC
Keating et al. 2001	1.2–0.8	7°	3.7×10^{-5}	$\delta = +43$
<i>Circular polarisation</i>				
Partridge et al. 1988	6.0	18''–160''	$\leq (2.2\text{--}0.6) \times 10^{-4}$	$\delta = +80$
Lubin et al. 1983	0.91	15°	$\leq 4 \times 10^{-3}$	$\delta = +37$

a few degrees, reionisation modifies α by order of magnitudes (see Figure 1).

- 3) to disentangle scalar, vector (vortices) and tensor modes of matter density perturbations.
- 4) to detect small deviations from uniform expansion and the existence of rotational modes in the universe.

Only the last condition can produce circular polarisation. All the remaining effects are associated with linear polarisation, although different patterns for the field distribution (E and B modes) are associated with different modes of the matter density perturbations which give rise to polarisation.

Between the discovery of the CMB in 1964 and the beginning of the 1980s many attempts to detect linearly or circularly polarised components of the CMB were made. The results are listed in Table 1: because different authors quote their results in different ways we used the published results to work out, and quoted in Table 1, the polarisation degree, calculated assuming an absolute temperature of the CMB of 2.73 K.

However, discouraged by negative results and by the absence of firm indications of the expected degree of polarisation, observers gradually abandoned the search for polarisation in favour of anisotropy. At the beginning of the 1990s, when CMB anisotropies were finally detected at levels of few tens of μK by COBE–DMR (Smoot et al. 1992), polarisation studies gained new momentum.

The COBE–DMR results however made clear that the CMB polarisation had to be searched for at levels of a few μK or less, levels extremely close to the polarised signals produced by the foreground (Galactic synchrotron radiation, blend of extragalactic radiosources, dust emission) one inevitably sees when one looks at the sky with a radiometer and well below the level of spurious polarisation produced by common polarimeters. New sophisticated systems of detection were therefore devised and stringent upper limits are now appearing in

the literature (see references in Table 1). In Table 1 we quote the measured upper limits (95% confidence limit) to the degree of polarisation Π . Because different authors give different quantities (U , Q , V , $\sqrt{U^2 + Q^2}$, Π), when not available we obtained Π from $\Pi = \sqrt{U^2 + Q^2}/T_{\text{CMB}}$ or, when just one of the Stokes parameters (U or Q or V) is quoted, from $\Pi = 1.4 U(Q)/T_{\text{CMB}}$ with $T_{\text{CMB}} = 2.73$ K.

The angular scale $\theta \sim 2^\circ$ is a turning point in the distribution of the anisotropy and polarisation power spectra versus θ (see Figure 1). Sky regions whose extension is $> \sim 2^\circ$ are not causally connected unless we add inflation to Big Bang cosmology and the power spectrum of the anisotropies associated with them is practically constant while the polarisation power spectrum decreases as θ increases. Therefore α decreases as θ increases, but the rate at which α decreases is reduced if the thermal history of the universe included reionisation some time between $Z \simeq 1000$ and now. Below $\sim 2^\circ$, on the contrary, the regions are causally connected, the amplitudes of anisotropy and polarisation oscillate as θ varies and α is close to 0.1.

2 The Milano Polarimeter

The Milano Polarimeter was built for ground based observation of the CMB. This dictated the observing frequency (33 GHz): sufficiently high to minimise the Galactic synchrotron signal and sufficiently low to reduce absorption and emission by the atmospheric layers above the radiometer.

Because the expected signal is comparable to or even smaller than the spurious polarised signals produced by optics, hardware, or electrical asymmetries, by the environment and by the sky foreground, we decided to exclude reflectors and to point a simple corrugated horn directly at the sky. This carries low angular resolution ($\Delta\theta > 5^\circ$), so we chose 7° , the angular resolution of COBE–DMR. Moreover, to recognise contamination by

the highly anisotropic polarised component of the Galactic background, we introduced the possibility of changing the antenna beam from 7° to 14° by eliminating the upper section of the horn. For similar reasons, moving parts and system movement were completely eliminated.

A two-channel etherodyne correlation receiver allowed us to extract a pair of Stokes parameters (Q and U or U and V) from the sky signal without moving the antenna. The receiver is fed by an Orthomode Transducer (OMT) which splits the signal collected by the antenna into two components with opposite polarisation. By inserting an iris polariser between horn and OMT one can choose between linearly or circularly polarised components.

Properly amplified and converted to 3 GHz in the two channels of the receiver, which uses two mixers driven by the same local oscillator to preserve the phase difference between the signals, these components go to a correlator, a combination of a hybrid phase discriminator (HPD), differential amplifiers and time integrators. The outputs of the correlator are linear combinations of Stokes parameters

$$\begin{bmatrix} O_1 \\ O_2 \end{bmatrix} = \begin{bmatrix} \langle S_1 \rangle \\ \langle S_2 \rangle \end{bmatrix} = \begin{bmatrix} K(Q \cos(\psi) - U \sin(\psi)) \\ K(Q \sin(\psi) + U \cos(\psi)) \end{bmatrix} \quad (2)$$

or

$$\begin{bmatrix} O_1 \\ O_2 \end{bmatrix} = \begin{bmatrix} \langle S_1 \rangle \\ \langle S_2 \rangle \end{bmatrix} = \begin{bmatrix} K(U \cos(\psi) - V \sin(\psi)) \\ K(U \sin(\psi) + V \cos(\psi)) \end{bmatrix} \quad (3)$$

where ψ is the phase difference produced by differences in the electrical lengths of the two receiver channels. Adjusting ψ one can separate the parameters. The choice between the pair (U , Q) and the pair (U , V) depends on the polarisation of the signals available at the OMT output. If the antenna signal is split in circularly polarised components the polarimeter outputs are U and Q , therefore we extract the linearly polarised fraction of the sky radiation. If the antenna signal is split in linearly polarised components the polarimeter outputs are U and V , therefore we measure the circularly polarised fraction of the sky radiation.

To guarantee a noise figure sufficient to detect a signal of a few parts in 10^6 the system front end (HEMT pre-amplifiers and lossy parts of the antenna: horn throat, iris polariser, and OMT) is cooled to 20 K by a mechanical cryocooler. A complete description of the system has been given elsewhere (Sironi et al. 1998b).

A prototype (Model Mk1), whose front end was only partially cooled to 77 K, was tested during the (local) summer at Terra Nova Bay (Antarctica). In spite of the limited period of time which was dedicated to observation we obtained upper limits $\Pi < 10^{-4}$ and $\Pi < 8 \times 10^{-5}$ to the degree of linear polarisation on a circle centred on the South Celestial Pole (SCP) with a diameter respectively of 7° and 14° (Sironi et al. 1998a). It showed that, when properly cooled, the Milano Polarimeter has a sensitivity

$$\Delta T_{\min} = 2.1 \times 10^{-3} \text{ K}/\sqrt{t(s)}$$

per channel sufficient to detect a $2 \mu\text{K}$ polarised signal in 12 days.

The complete system (Mk2) has then been tested at Dome C (Antarctica) during the local summer 1998/99 observing an annulus 7° wide, centered on SCP, along $\delta = -75^\circ$. Unfortunately a failure of the cryocooler forced us to stop observations a few days after the system was ready to observe (Zannoni 1999).

Back to Milano we further improved the system performance adding:

- 1) $(0 - \pi)$ phase modulation and synchronous detection which eliminates system offsets and the (dominant) fraction of $1/f$ noise produced in the receiver section which is enclosed between the modulator and the phase sensitive detector (see Figure 2). The expected noise rejection is

$$r = \frac{\sigma_{\text{locked}}}{\sigma_{\text{unlocked}}} = \sqrt{\frac{\frac{\ln(\nu_0 - 1/T)}{\ln(\nu_0 - 1/\tau)} + \frac{\ln(\nu_0 + 1/\tau)}{\ln(\nu_0 + 1/T)}}{2 \ln(T/\tau)}} \quad (4)$$

where σ_{locked} and σ_{unlocked} are the noise level one measures when the synchronous detector is locked and unlocked respectively, ν_0 is the modulation frequency, τ is the system time constant, and $T \gg 5\tau$ is the observing time. For $\tau = 1$ sec, $T = 10$ min, $\nu_0 = 256$ Hz we get $r = 4 \times 10^{-3}$ (for a complete discussion see Spiga 2000 and Spiga et al. 2001);

- 2) a thermal shield, made with a tent which completely surrounds the polarimeter, the associated electronics, and the cryocooler, creating a stable environment with a temperature of about 20°C (see Figure 2). It improves the system stability and protects the electronics and cryocooler against the extremely severe conditions one can find at high mountain sites or on the Antarctic Plateau.

3 Observational Program and Conclusion

The present version (Mk3) of the Milano Polarimeter is now ready for observation. As said above, at angular scales of 7° and 14° the expected signal is almost certainly below $1 \mu\text{K}$, therefore is undetectable by the majority of the present experiments, including our experiment, unless the thermal history of the universe included reionisation. This fact was not evident when we began our search, before COBE-DMR results were published. However because a detection or a firm upper limit at levels of a few μK is sufficient to decide for or against reionisation, we decided to continue with our original program of observations at large angular scales.

Meanwhile we are preparing observations at angular scales $\leq 2^\circ$ coupling our polarimeter to a 2 m class telescope, like the MITO Telescope (De Petris et al. 1996) at Testa Grigia on the Italian Alps, or the 2.6 m telescope proposed for Dome-C (Antarctica) by Giorgio Dalloglio (G. Dalloglio 2001, private communication) which is in preparation. The coupling optics, similar to those developed by our group for observation with SIS receivers (Battistelli 2002), will allow us to explore the 2° to $\sim 0.1^\circ$ region of angular scales. Attention is however necessary to avoid spurious polarisation: many tests and ancillary

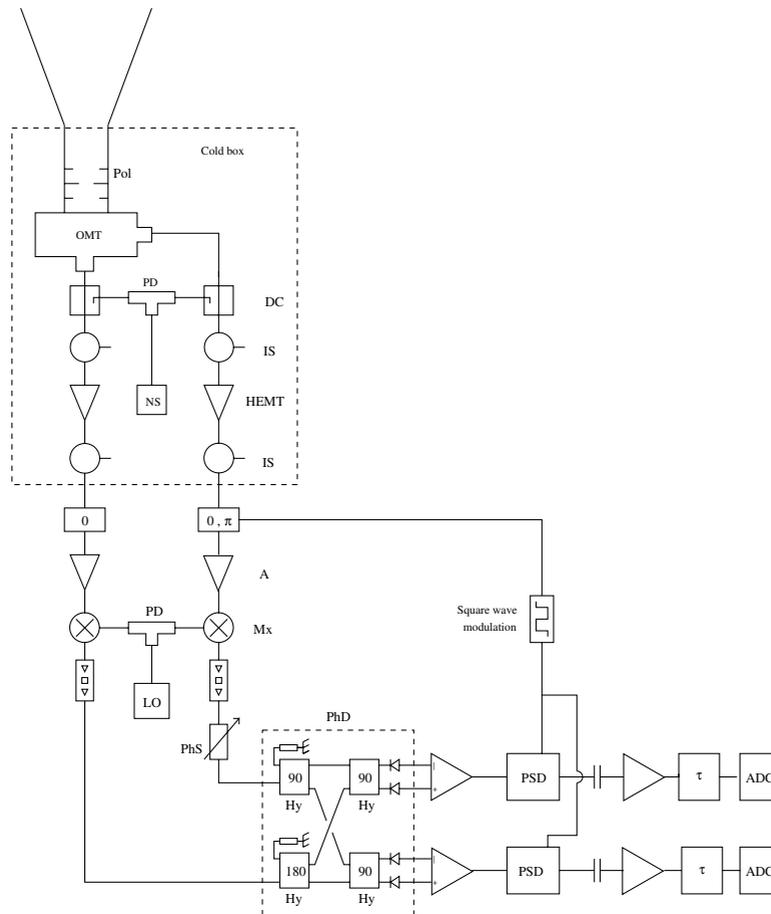


Figure 2 Mk3 block diagram. Cold box: vacuum tank at 20 K, Pol = iris polariser, OMT = Orthomode Transducer, PD = Power Divider, DC = Directional Coupler, IS = Isolator, HEMT = Cryogenic Low Noise Amplifier, NS = Noise Source, LO = Phase Locked Local Oscillator, Mx = Mixer, PhS = Adjustable Phase Shifter, PhD = Phase Discriminator, Hy = Hybrid circuit, PSD = Phase Sensitive Detector, τ = time integrator, ADC = Converter, $[0 - \pi]$ = phase switch.

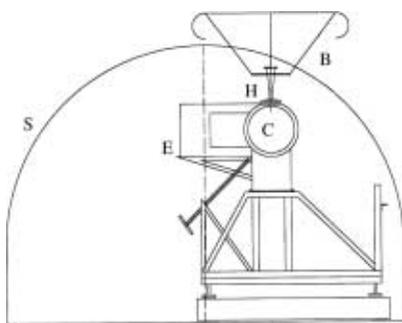


Figure 3 The shelter which protects the Mk3 Milano Polarimeter. B = Baffle, H = Horn, C = Cold box (20 K), E = Room temperature electronics, S = Polar tent. A system of heaters and coolers creates room temperature conditions with maximum temperature variations of $\pm 2^\circ\text{C}$ even in harsh weather conditions.

observations will be made before astronomical observations. We are preparing also a small (1.5 m diameter) dish to be coupled to our polarimeter for observations in transit mode with an angular resolution of 2° , the angular scale at which anisotropies are at a maximum, if the above telescopes are not available.

Mk3 is at present on the roof of the Physics Department in Milano where it is used as a transit instrument with the beam aimed at the zenith for systematic tests. The atmosphere above Milano is definitely bad but in principle, as shown by results obtained by other groups at low elevation in populated areas like Berkeley, Princeton, or Madison (see references in Table 1), atmosphere does not affect polarisation, therefore one cannot exclude that we will obtain astronomically significant data at $\delta = +45^\circ$, with angular resolutions of 7° and 14° both in linear and circular polarisation.

At the end of 2001 we will take the polarimeter to Testa Grigia on the Italian Alps (3500 m above sea level). First of all we will observe in transit mode, with low angular resolution (7° – 14°), regions of sky between $\delta = +45^\circ$ and the North Celestial Pole (NCP). We will then test the 1.5 m small dish observing in transit mode with angular resolution of 2° the NCP region. Finally we plan to attach the polarimeter to the MITO telescope and to observe, in tracking mode, toward the NCP, spots selected on anisotropy maps prepared for instance by the recently launched space experiment MAP (MAP 1998).

As soon as the Antarctic French Italian Base of Dome C (Sironi 1998) opens for winter observations we are ready to install the system at Dome C for systematic observations of the region around the SCP, taking advantage of the superb transparency and stability of the atmosphere at mm wavelengths on the Antarctic Plateau. During the six months of darkness, using the system in transit mode, we expect to reach a limit of $2 \mu\text{K}$ on the SCP and at least four spots on a circle around it at $\delta = -80^\circ$ with angular resolution of 7° and 14° in linear polarisation. We will then observe in circular polarisation. If a 2 m class telescope is available at Dome C, we are ready to attach our polarimeter to it for observations, the following winter, of sky spots selected on the Boomerang (De Bernardis et al. 2000) and MAP (MAP 1998) anisotropy maps. If not, we will carry out observations at $\sim 2^\circ$ angular scale in transit mode with the 1.5 m fixed parabola. It is highly probable that, during the stay of our system at Dome C, SPORt (Cortiglioni et al. 1999), a space experiment on the International Space Station for measurements between 20 and 100 GHz of the polarisation of the sky diffuse radiation, will be in operation. A comparison between data obtained in extremely different conditions will be useful both for intercalibrations and for recognising systematic effects.

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