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Considerations about a space mission devoted to CMB polarization

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We describe the main drivers and problems for a high accuracy space-borne survey of CMB polarization with cryogenic bolometers. While the possibility to detect a signature of inflation is very important, both for cosmology and for particle physics, the required survey sensitivity and control of systematics and foregrounds are extremely challenging. New instrumental devices, including *e.g.* large format detector arrays and extremely clean polarization modulators, must be developed and tested in a series of preliminary ground-based and space-borne experiments, to face these challenges.

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1. Introduction

Measuring the B-modes of CMB polarization is extremely interesting and extremely difficult. According to the inflationary paradigm (see e.g. [2, 3, 4, 5]), a stochastic background of gravitational waves is generated in the very early universe. These produce a characteristic linear polarization pattern in the CMB, with both rotational (B-modes) and curl-free (E-modes) components. The other effect inducing linear polarization in the CMB is the presence of velocity gradients of the primeval fireball produced by density fluctuations at recombination. Since density fluctuations do not produce rotational polarization, the B-mode polarization is a signature of Inflation (see e.g. [6, 7]). B-modes polarization from inflationary gravitational waves is expected at a very low level, lower than 100 nK ([10, 11]). From the amplitude of the tensor component in CMB polarization it is possible to infer the energy scale E_{infl} of the inflation process:

$$E_{infl} \sim 3 \times 10^{-3} m_{Planck} \left(\frac{T}{S} \right)^{\frac{1}{4}} \tag{1.1}$$

Alternative early universe scenarios, like the cyclic model of [8], do not produce B-modes at all ([9]). Inflation is the main candidate to solve the paradoxes of standard hot big bang cosmology, and its observable characteristics would provide unique windows on the physics of ultra high energies, which cannot be investigated in the laboratory. Current upper limits on the tensor component ($T/S \lesssim 0.4$) already suggest that inflation is not related to Quantum Gravity or String Theory phenomena ($E \sim 10^{19} GeV$). Obtaining a detection would point to an underlying GUT, SUSY or PQ: this explains the wide interest of the Cosmology and of the Particle Physics communities on this subject. There are, however, two competing effects producing B-modes polarization in the mm-wave sky: the conversion of E-modes into B-modes due to weak gravitational lensing from cosmic structures. and the presence of galactic and extragalactic polarized foregrounds. Lensing can be monitored if the polarization survey has sufficient angular resolution; however, it is recognized that it will be practically impossible to detect the tensor component if the energy scale of inflation is less than $E \sim 10^{15} GeV$.

Current technology provides measurements of polarized CMB at a level of a few μK (see e.g. [1] and references therein). To explore the full range of energies of interest, not only a $\gtrsim 100\times$ improvement in raw sensitivity is required, but also the purest possible front-end optics, and a clean strategy to disentangle systematic effects and polarized foregrounds at such a faint level.

An intense research and development work is underway in many laboratories worldwide. A satellite mission is present in the Beyond Einstein program of NASA and in the Cosmic Vision program of ESA. In Italy, a coordinated study aimed to exploit CMB polarization science has been funded by ASI (Italian Space Agency). This study has devised a sequence of experimental, theoretical and interpretation activities. Further study is required: we believe, in fact, that we are not ready yet for the final design of a CMB polarization space mission. We want, instead, carry out a sequence of experiments to refine the polarization detection techniques.

In the following we focus on the three main problems of a mission devoted to B-modes.

2. Foregrounds

Foreground emission is ubiquitous even at high Galactic latitudes, as evident from the all-sky

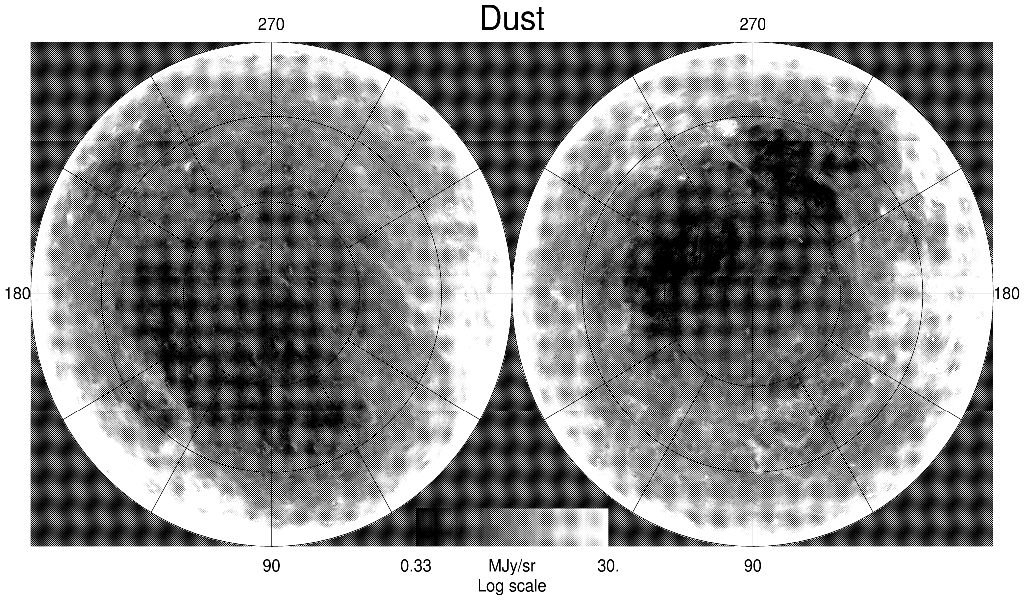

Figure 1: Dust emission at a frequency of 3000 GHz, as measured from the IRAS full sky survey (figure from Finkbeiner et al., 2002, http://astro.berkeley.edu/davis/dust/images/images.html). Cirrus dust is evidently ubiquitous. There are, however, two reasonably clean (dark) regions, one in each hemisphere (about 40% of the sky) which are likely to be used for CMB polarization studies.

map of IRAS, monitoring patchy emission from interstellar dust even at high Galactic latitudes. This map was obtained at a frequency ten times higher than the ones of interest here. In fig.1 we plot such emission and show the two sky regions of minimum contamination, which are likely to be used by a B-modes polarization survey.

Direct measurements of the polarized foreground at high galactic latitudes, in the 40-250 GHz range of interest here, are not easy. The main problem is that in these conditions fluctuations in the polarized foreground are smaller than CMB anistropy. Most of the information comes from extrapolation of surveys at wavelengths outside the 40-250 GHz range, where foreground emission is prominent. However, extrapolation is difficult. Synchrotron emission is intrinsically highly polarized [12] and dominant at long wavelengths. Its spectral index steepens at shorter wavelengths, and has poorly known variations from region to region of the high latitude sky (see e.g. [13]). The surveys at very low frequencies ([14], [15], [16], [17], [18], [19]) are affected by Faraday rotation, depolarization and other astrophysical effects (see e.g. [20]), so extrapolation to our range is very uncertain. In the latest analysis of WMAP data, it was found that at large angular scales the polarized foreground is dominated by synchrotron, and in the range from 20 to 60 GHz is from 10 to 2 times stronger than the E-modes of CMB polarization [21].

Free-free emission has a well known spectrum, milder than the synchrotron one. Templates have been obtained studying the interstellar Hα emission [22], [23]. The free-free emission process does not produce polarized radiation (unless very anisotropic and dense regions are considered), so it is disregarded in the computation of the polarized foreground.

For interstellar dust emission the extrapolation of unpolarized brightness is based on the IRAS and DIRBE data (see e.g. [25], [26], [27], [28]). These extrapolations fit quite well the observed

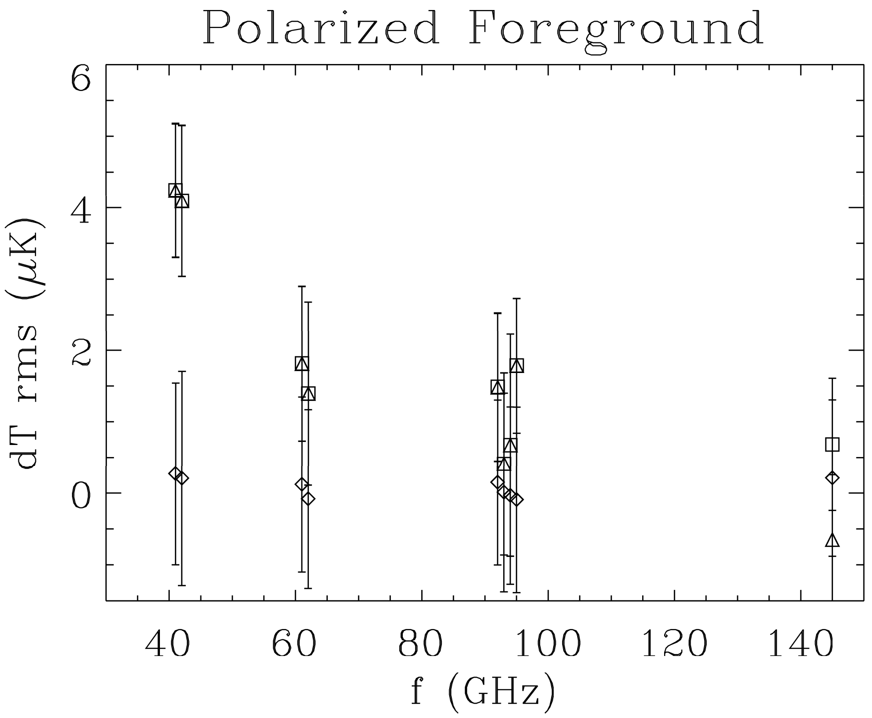

Figure 2: Rough estimate of the polarized foreground at high galactic latitudes: squares represent the total rms fluctuation, the triangles the synchrotron component, the diamonds the dust component. (see text)

emission pattern observed at high latitudes [24]. Information about interstellar dust polarization in absorption comes from sparse data of starlight polarization [29]. Only recently polarized emission of diffuse interstellar dust at mm wavelengths was detected [30], [31]: the level of polarization is at most 10% and usually $\lesssim 5\%$, consistent with optical polarization measurements. Its polarization pattern has both E-modes and B-modes. Since we know very little about the configuration and distribution (especially the fine structure) of the Galactic magnetic field aligning the dust grains, extrapolation is good only for order of magnitude arguments. We know that at 150 GHz at high latitudes the power spectrum of dust emission is about 1% of the power spectrum of CMB anisotropy [24]. So we naively expect B-modes from dust polarization power spectrum at a level of 0.01% of the anisotropy. Enough to say that this will be an important foreground for the B-modes of the CMB, whose level is also $\lesssim 0.01\%$ of anisotropy !

In fig. 2 we give a crude estimate of the polarized foreground starting from the unpolarized intensity maps from WMAP (41, 62, 94 GHz) and from BOOMERanG (145 GHz), at high Galactic latitudes (the clean region observed by BOOMERanG-B03, see [1]). All the maps are filtered to sample angular scales between $\sim 20^o$ and $\sim 0.5^o$. For each frequency, the map is compared to a synchrotron template (WMAP 21 GHz map) and to a dust template (IRAS-DIRBE map), and the rms of the correlated component is computed. Then 10% of the estimated dust rms and 50% of the estimated synchrotron rms are added in quadrature, to form a rough estimate of the rms of the polarized foreground. This is of the order of $\sim 1-2\mu K$ at $\nu < 100 GHz$, and $\lesssim 1\mu K$ at 150

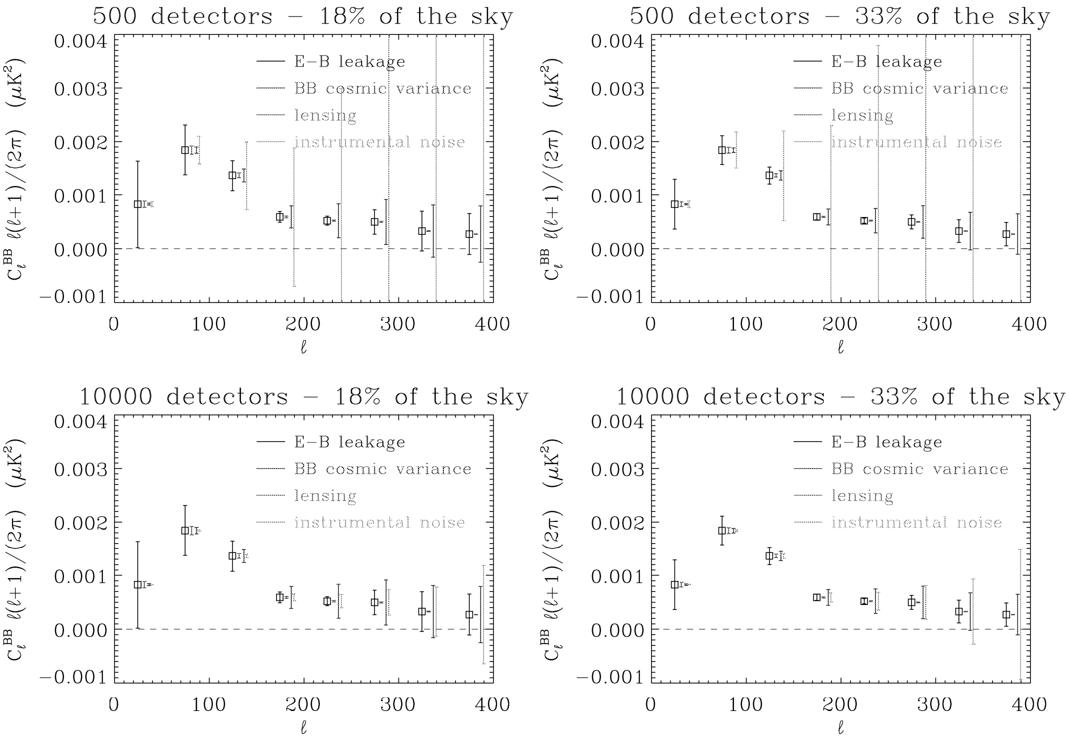

Figure 3: Simulated measurement of the B-polarization power spectrum during a 1 year survey of 18% (left) or 33% (right) of the sky, using a space-borne mission with 500 (top) or 10000 (bottom) polarization sensitive detectors with $NET_{CMB} \sim 150\mu K/\sqrt{Hz}$. The data (squares) correspond to a model with a tensor to scalar ratio $r = 0.03$. Four error bars are plotted for each data bin: these represent the uncertainty resulting from (left to right) leakage of E-modes into B-modes due to finite sky coverage; cosmic variance of the B-modes; B-modes from lensing; instrumental noise.

GHz. The minimum contamination, in this clean region, is somewhere in the 100-170 GHz range. Averaging over a wider sky coverage, the minimum of the polarized foreground is at $\nu \sim 75GHz$ [21]. It is evident that better foreground measurements are needed to design a mission devoted to precision polarization measurements. In the following we will assume that at most 50% of the sky can be used for B-modes measurements, and that a frequency coverage from 30 GHz to 300 GHz is necessary for an accurate control of the foreground polarization.

3. Sensitivity

Photon noise of the CMB limits the ultimate sensitivity achievable for a CMB survey (CMB-BLIP). The NET_{CMB} corresponding to CMB photon noise is of the order of $30\mu K/\sqrt{Hz}$ in a diffraction limited 10% band around 150 GHz , and about $50\mu K/\sqrt{Hz}$ in a diffraction limited 10% band around 30 GHz. Current bolometer technology provides low background detectors cooled at 0.1K with a NEP of $\sim 80\mu K/\sqrt{Hz}$. Very soon bolometers operating in low background conditions will operate in CMB-BLIP conditions. In such a situation, the only way to improve the efficiency of a CMB survey will be to increase the number of detectors mapping simultaneously different areas

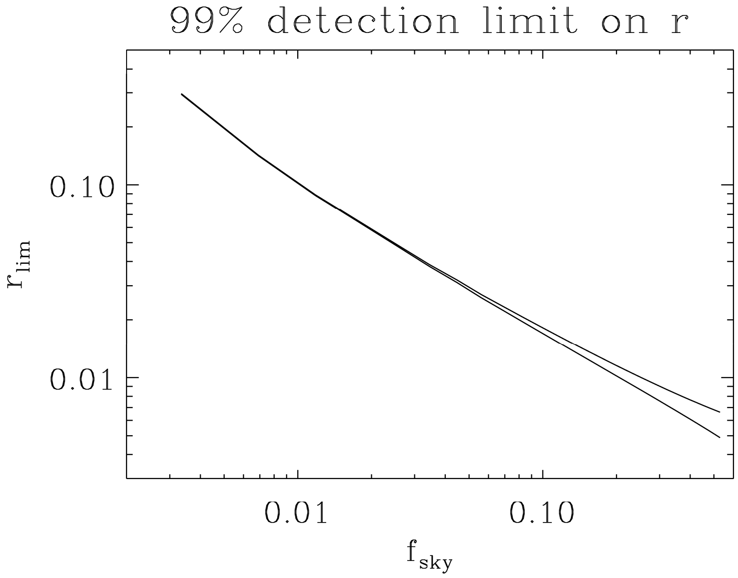

Figure 4: Detection limit for the estimate of the tensor to scalar ratio obtained from the measurements of the B-polarization power spectrum. The survey conditions are the same as in the previous figure. The upper line corresponds to 500 detectors, the lower line to 10000 detectors. For a sky coverage lower than 10% the uncertainty in the correction for leaking and the cosmic variance of B-modes are the dominant sources of error.

of the sky, i.e. to use a large-format array of detectors. Bolometer arrays fabricated on Si wafer are already being produced (see *e.g.* Bock, these proceedings, [33] and [32]). The technology of Transition Edge Superconducting bolometers with SQUID multiplexer readout, being easily scalable at very large array sizes, seems to be the most suitable for a satellite mission. A competing technology, in a somewhat less advanced development phase, is the MKID detector [34].

In fig. 3 we show how the measurement of the power spectrum of the rotational modes of CMB polarization is affected by sky coverage and integration time. In the simulations we follow the calculations of [35]. We have assumed to have either 500 or 10000 ideal detectors in the focal plane (or in multiple focal planes). Each bolometer is sensitive to a single polarization, with a NET_{CMB} of $\sim 150\mu K/\sqrt{Hz}$. Real world effects like spikes, 1/f noise and uneven sky coverage are neglected. Most of the B-modes signal from inflation is at medium and large angular scales, so we assumed a beam FWHM of 0.5^o for all the detectors. In the figures we have assumed a tensor to scalar ratio $r = 0.03$, and we plot fiducial measurements affected by four kinds of uncertainty: Uncertainty in the leakage of E-modes into B-modes due to finite sky coverage; cosmic variance of the B-modes; B-modes from lensing; instrumental noise. From the figure it is evident that most of the signal comes from scales $\ell \lesssim 200$. Here the effect of detector noise is negligible with respect to the other sources of uncertainty already with a "small" focal plane including 500 detectors. The same can be seen in fig. 4, where we plot the uncertainty in the estimate of r obtained from a Fisher matrix analysis. It is evident that it will be anyway extremely difficult to obtain a detection of $r \lesssim 0.001$.

4. Systematics

BOOMERanG-03 ([1], [36], [37]) has shown that systematic effects can be controlled by a combination of multifrequency capabilities, scan speed and inclination variations, polarization angle redundancy, variations of observing conditions, accurate pre-flight and in-flight calibration. This was OK at the level of sensitivity of B03 (i.e. a few σ detection of E-modes, $\sim 4\mu K$ rms). Nobody knows how to control systematics for a B-modes experiment ($< 0.1\mu K$ rms). The only way is to experiment ! Polarized calibration sources must be found and characterized. Clean polarization modulators are necessary and need to be tested in space conditions. The most elementary modulation consists in scanning the sky with independent detectors sensitive to orthogonal polarizations. This has been used in BOOMERanG and WMAP, and will be used in Planck. A variation of it is to spin the full instrument (like in the proposed SAMPAN instrument, see Bouchet et al, these proceedings). This is, however, sensitive to anisotropy in the sidelobes of the instrument. Adding one modulator device (like in MAXIPOL, QUAD, etc.) is sensitive to microphonics (for mechanically actuated modulators, like rotating waveplates or polarizers), and to non-ideality of the device (for mechanically and electrically actuated devices). We really need to experiment more. In this sense, Planck and the forthcoming balloon borne experiments like EBEX ([38]), PILOT ([39]) and the new BOOMERanG will provide a lot of experience of instrument performance in space conditions.

5. Conclusions

The main problems in the detection of inflationary B-modes in CMB polarization are the development of large format arrays of polarization-sensitive microwave detectors, the development of clean and reproducible polarization modulators, and the ability to sense and separate polarized foregrounds. Despite of all the challenges described above, there is strong interest in Italy about CMB polarization science, and in particular about a space-based mission devoted to B-modes. This "B-pol" mission has been rated top priority in the COFIS study (Cosmology and Fundamental Physics from Space) carried out by the Italian cosmology community in 2004 (see http://oberon.roma1.infn.it/lezioni/cofis/). The Italian Space Agency has been ad has promised to continue to be supportive of these efforts. Enabling technologies are being developed also in Italy; we are very active in sub-orbital experiments, and eager to participate in a European development in the framework of the ESA Cosmic-Vision program.

References

[1] Masi S., et al., 2005, Astronomy and Astrophysics, in press, astro-ph/0507509

[2] Mukhanov V.F., Chibisov G.V., 1981, JETP Lett., 33, 532-535 (1981, Zh. Eksp. Teor. Fiz., 33, 549-553) see also astro-ph/0303077

[3] Guth, A., & Pi, S. Y., 1982, Phys. Rev. Lett., 49, 1110

[4] Linde, A., 1983, Phys. Lett., B129, 177.

[5] Kolb, E.W., and Turner, M.S., The Early Universe, Addison-Welsey, 1990.

[6] Copeland, E.J., Kolb, E.W., Liddle, A.R., and Lidsey, J.E. , 1993, Phys. Rev. Lett., 71, 219 ; 1993, Phys. Rev. D, 48, 2529.

[7] Turner, M.S., 1993, Phys. Rev. Lett., 71, 3502; 1993, Phys. Rev. D., 48, 5539.

[8] Steinhardt, P.J., Turok, N., 2002, Science, 296, 1436

[9] Boyle, L.A., Steinhardt, P.J., Turok, N., 2004, Phys.Rev. D70, 023504

[10] Leach, S.M.,Liddle, A.R., 2003, Phys. Rev., D68, 123508

[11] Song, Y.S., Knox, L., 2003, Phys. Rev., D68, 043518

[12] Rybicki G.B., and Lightman A., 1979, Radiative Processes in Astrophysics (Wiley & Sons, New York)

[13] Bennett, C., et al., 2003, ApJS, 148, 1

[14] Brouw W.N., Spoelstra T.A., 1976, Astron. Astrophys. Suppl. Ser., 26, 129

[15] M. Wolleben, T. L. Landecker, W. Reich, R. Wielebinski, 2005, Astronomy and Astrophysics in press, astro-ph/0510456

[16] A. Duncan, R. Haynes, R.F. Jones, R.T. Stewart, 1995, MNRAS, 277, 36

[17] A. Duncan, P. Reich, W. Reich, E. Furst, 1999, Astron. Astrophys., 350, 447

[18] Uyaniker B., Fuerst E., P. Reich, W. Reich, R. Wielebinski, 1999, Astron. Astrophys. Suppl. Ser. 138, 31

[19] Bernardi, G., et al., 2003, Ap.J.Lett., 594, 5

[20] Cortiglioni S., Spoelstra T., 1995, Astron. Astrophys., 302, 1

[21] Page L., Three Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Polarization Analysis, astro-ph/0603450 [abs, ps, pdf, other] :

[22] Gaustad J.E., Mc Cullough P.R., Rosing W.R. & Buren D.V., 2001, PASP 113, 1326

[23] Haffner L.M., Reynolds R.J., Tufte S.L. et al. 2003, astro-ph/0309117

[24] Masi S., et al., 2001, Ap.J. 553, L93

[25] Finkbeiner, D., Davis, M., & Schlegel, D., 1999, Ap.J., 524, 867

[26] Schlegel D.J. et al. 1999, Ap.J. 500, 525.

[27] Finkbeiner D., Schlegel D.J, Frank C.& Heiles C., 2002, ApJ 566, 898

[28] M. Miville-Deschenes, G. Lagache, IRIS: A new generation of IRAS maps, ApJ (Suppl), in press, 2004, astro-ph/0412216

[29] Heiles C. 2000, ApJS, 111, 245

[30] Benoit A., et al., 2004, Astron.Astrophys. 424, 571

[31] N. Ponthieu, et al., 2005, Astron.Astrophys. 444, 327

[32] Lee, A.T., et al., 1996, Appl. Phys. Lett. 69, 1801

[33] Orlando, A., et al., 2006, NIM, 599A, 534

[34] Day, P.K., et al., 2003, Nature 425, 777 - 778

[35] Challinor, A., Chon, G., 2005, Mon.Not.Roy.Astron.Soc., 360, 509-532

[36] Piacentini, F., et al., 2005, Ap.J., in press, astro-ph/0507507

[37] Montroy T., et al., 2005, Ap.J., in press, astro-ph/0507514

[38] Hanany S., et al., Proc.SPIE, 2004, 5543, 320-331, astro-ph/0501111

[39] Bernard J.P. et al., 2005, Proc. of the Polarisation 2005 conference, EAS Publication Series EDP sciences, Paris, in press.