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Ground-based and Airborne Telescopes IV

Larry M. Stepp
Roberto Gilmozzi
Helen J. Hall
Editors

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Introduction

The large number of submissions to and excellent attendance at the Ground-based and Airborne Telescopes IV conference reflects the strong and growing interest in the astronomical and engineering communities. More than 250 papers were submitted to this year's conference, the largest number in the series' history. This year's conference included 28 oral sessions and two poster sessions.

Good progress was reported on many ongoing and planned programs. Excellent invited papers were presented on ALMA, ASKAP, ATST, CTA, DCT, DOT, E-ELT, FAST, GMT, KDUST, LMT, LOFAR, LSST, MeerKAT, NST, SKA, SOFIA, and TMT.

The technical subjects covered in the papers are similar to previous conferences, with some evolution of emphasis. Papers were presented on many current and proposed optical-IR telescope projects, and attendance was strong as always in the session on the ELT projects. Many aspects of telescope design were covered, including structures and enclosures, control systems, active optics, thermal and vibration control, and alignment and control of segmented mirrors.

We heard reports on several solar telescope projects in two conference sessions, one of which was devoted to ATST. There were two sessions on airborne telescopes, with one devoted to SOFIA, which has recently started science operations. The increasing importance of survey telescopes was evident with two sessions devoted to telescopes for synoptic and survey observations. Another area of increased interest is gamma ray telescopes, which also had its own session at this conference.

Development of new radio telescopes remains a strong area, occupying one full day in the conference. The progress of SKA was reflected in a separate SKA session with four invited papers. Millimeter and submillimeter telescopes filled two sessions, with one session devoted to ALMA, which has started science operations this year.

It is clear that our understanding of the properties of astronomical sites is continuing to improve, and there is a growing interest in the design of telescopes to operate in extreme environments, particularly the Arctic and Antarctic. Another area of increasing interest is the design of telescopes to withstand earthquakes, with new approaches presented at the conference.

The chairs would like to thank the SPIE symposium organizers, the GB&AT program committee, the session chairs, the authors and all the conference participants for making this year's conference so successful.

Larry M. Stepp
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The cosmic microwave background: observing directly the early universe

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ABSTRACT

The Cosmic Microwave Background (CMB) is a relict of the early universe. Its perfect 2.725K blackbody spectrum demonstrates that the universe underwent a hot, ionized early phase; its anisotropy (about 80 μK rms) provides strong evidence for the presence of photon-matter oscillations in the primeval plasma, shaping the initial phase of the formation of structures; its polarization state (about 3 μK rms), and in particular its rotational component (less than 0.1 μK rms) might allow to study the inflation process in the very early universe, and the physics of extremely high energies, impossible to reach with accelerators. The CMB is observed by means of microwave and mm-wave telescopes, and its measurements drove the development of ultra-sensitive bolometric detectors, sophisticated modulators, and advanced cryogenic and space technologies. Here we focus on the new frontiers of CMB research: the precision measurements of its linear polarization state, at large and intermediate angular scales, and the measurement of the inverse-Compton effect of CMB photons crossing clusters of Galaxies. In this framework, we will describe the formidable experimental challenges faced by ground-based, near-space and space experiments, using large arrays of detectors. We will show that sensitivity and mapping speed improvement obtained with these arrays must be accompanied by a corresponding reduction of systematic effects (especially for CMB polarimeters), and by improved knowledge of foreground emission, to fully exploit the huge scientific potential of these missions.

Keywords: cosmic microwave backgorund, millimeter wave telescope, array of bolometers

1. INTRODUCTION

We live in an expanding universe, cooling down from a state of extremely high density and temperature, the big bang. In our universe the ratio between the density of photons (the photons of the cosmic microwave background) and the density of baryons is of the order of 10^9: this abundance of photons dominated the dynamics of the Universe in the initial phase (first 50000 years). During the first 380000 years the universe was ionized and opaque to radiation, due to the tight coupling between photons and charged baryons. Radiation thermalized in this primeval fireball, producing a blackbody spectrum. When the universe cooled down below 3000K, neutral atoms formed (recombination), and radiation decoupled from matter, traveling basically without any further interaction all the way to our telescopes. Due to the expansion of the universe, the wavelengths of photons expand (by the same amount all lengths expanded, a factor of 1100). What was a glowing 3000K blackbody 380000 years after the big bang, has been redshifted to millimeter waves, and is now observable as a faint background of microwaves. This is the cosmic microwave background, which has been observed as a 2.725K blackbody filling the present universe.[1]

The CMB is remarkably isotropic. However, it is widely believed that the large scale structure of the universe observed today (see e.g.[2]) derives from the growth of initial density seeds, already visible as small anisotropies in the maps of the Cosmic Microwave Background. This scenario works only if there is dark (i.e. not interacting electromagnetically) matter, already clumped at the epoch of CMB decoupling, gravitationally inducing anisotropy in the CMB. There are three physical processes converting the density perturbations present at recombination into *observable* CMB temperature fluctuations $\Delta T/T$. They are: the photon density fluctuations δ_γ, which can be related to the matter density fluctuations $\Delta\rho$ once a specific class of perturbations is specified;

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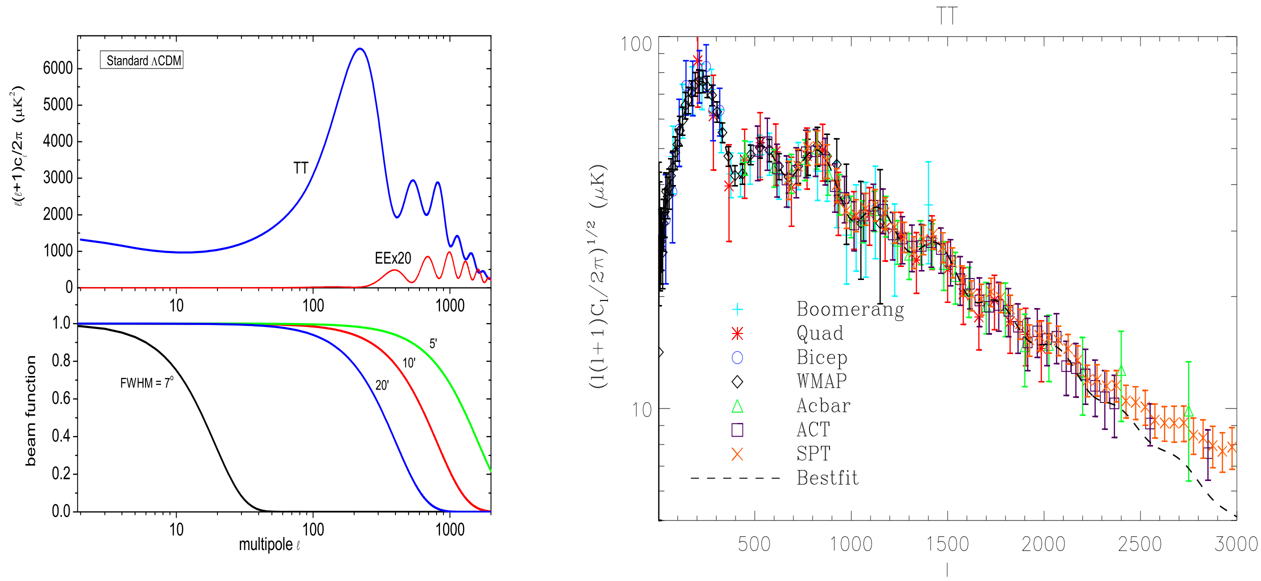

Figure 1. **Left-Top:** Angular power spectrum for CMB anisotropy (TT) and for EE polarization. The latter has been amplified 20 times to make it visible in the same plot of TT. The angular scale γ corresponding to multipole ℓ is approximately $\gamma(^o) = 180/\ell$. **Left-Bottom:** Filter functions of CMB telescopes with different angular resolutions. A FWHM smaller than 1^o is needed to be sensitive to the "acoustic peaks" due to photon-baryon oscillations in the early universe. The curves are labeled with the beam FWHM. Differential instruments will not be sensitive to multipoles $\ell < 180/\alpha(^o)$ where α is the angular separation of the beam switch; experiments scanning a limited sky region with angular size θ cannot be sensitive to multipoles with $\ell < 180/\theta(^o)$. **Right:** Selected recent measurements of the angular power spectrum of CMB anisotropy.

the gravitational redshift of photons scattered in an over-density or an under-density with gravitational potential difference $\Delta\phi_r$; the Doppler effect produced by the proper motion with velocity v of the electrons scattering the CMB photons. In formulas:

$$\frac{\Delta T}{T}(\vec{n}) \approx \frac{1}{4}\delta_{\gamma r} + \frac{1}{3}\frac{\Delta\phi_r}{c^2} - \vec{n} \cdot \frac{\vec{v_r}}{c} \tag{1}$$

where $\vec{n}$ is the line of sight vector and the subscript r labels quantities at recombination.

Our description of fluctuations with respect to the FRW isotropic and homogeneous metric is totally statistical. So we are not able to forecast the map $\Delta T/T$ as a function of (θ, ϕ), but we are able to predict its statistical properties. If the fluctuations are random and Gaussian, all the information encoded in the image is contained in the angular power spectrum of the map, detailing the contributions of the different angular scales to the fluctuations in the map. In other words, the power spectrum of the image of the CMB details the relative abundance of the spots with different angular scales.

If we expand the temperature of the CMB in spherical harmonics, we have

$$\frac{\Delta T}{T} = \sum a^T_{\ell,m} Y^m_\ell(\theta, \phi) \tag{2}$$

the power spectrum of the CMB temperature anisotropy is defined as

$$c^{TT}_\ell = \langle TT \rangle = \langle a^T_{\ell,m} a^{T,*}_{\ell,m} \rangle \tag{3}$$

with no dependence on m since there are no preferred directions. Since we have only a statistical description of the observable, the precision with which the theory can be compared to measurement is limited both by

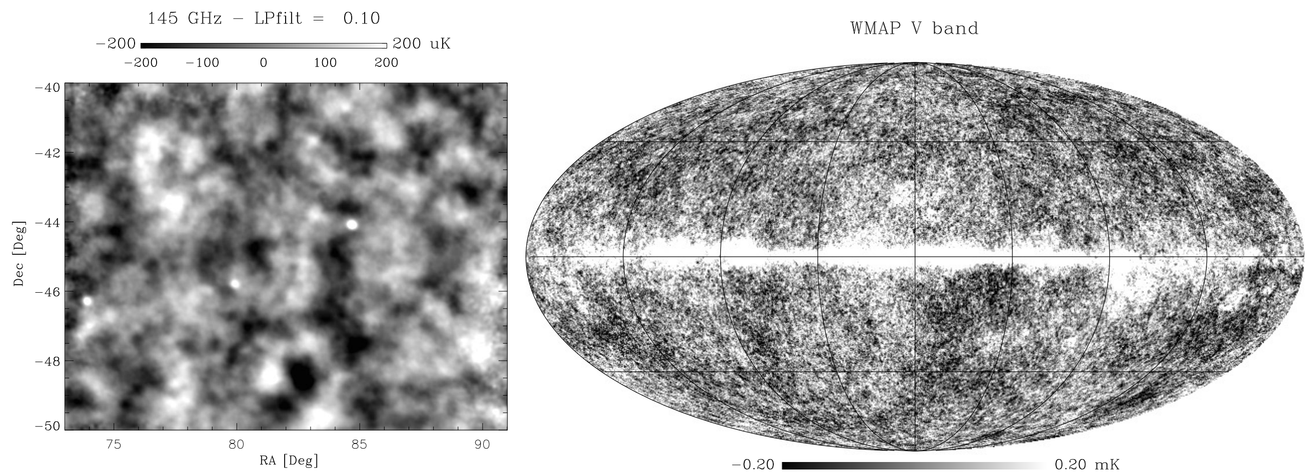

Figure 2. **Left:** The first map of the CMB with angular resolution and signal to noise ratio sufficient to resolve degree-sized causal horizons in the early universe was obtained by the BOOMERanG experiment, at 145 GHz, using an off-axis telescope flown on a stratospheric balloon.[11] The structures visible in the map are CMB anisotropies, while the contamination from local foregrounds and from instrument noise are both negligible. **Right:** The WMAP satellite has mapped the whole sky, confirming the ubiquitous presence of causal horizons, and allowing a precise determination of the power spectrum of CMB anisotropy and of the cosmological parameters.[12,13]

experimental errors *and* by the statistical uncertainty in the theory itself. Each observable has an associated cosmic and sampling variance, which depends on how many independent samples can be observed in the sky. In the case of the c_ℓs, their distribution is a χ^2 with $2\ell+1$ degrees of freedom, which means that low multipoles have a larger intrinsic variance than high multipoles (see e.g.[3]).

Theory predicts the angular power spectrum of CMB anisotropy with remarkable detail, given a model for the generation of density fluctuations in the Universe, and a set of parameters describing the background cosmology. Assuming scale-invariant initial density fluctuations, the main features of the power spectrum c_ℓ^{TT} are a $1/[\ell(\ell+1)]$ trend at low multipoles, produced by the Sachs-Wolfe effect[4] (second term in equation 1); a sequence of peaks and dips at multipoles above $\ell = 100$, produced by acoustic fluctuations in the primeval plasma of photons and baryons,[5–7] and a damping tail at high multipoles, due to the finite depth of the recombination and free-streaming effects.[8] Detailed models and codes are available to compute the angular power spectrum of the CMB image (see e.g.[9,10]). The power spectrum c_ℓ^{TT} derived from the current best-fit cosmological model is plotted in fig.1 (top panel).

High signal-to-noise maps of the CMB have been obtained since year 2000[11] (see fig.2). From such maps, the power spectrum of CMB anisotropy is now measured quite well (see e.g.[11,13–27] and fig.1, right panel); moreover, higher order statistics are now being measured with the accuracy required to constrain cosmological parameters (see e.g.[28]). Despite of the very small signals, the measurements from independent experiments, using diverse experimental techniques, are remarkably consistent. Moreover, an adiabatic inflationary model, with cold dark matter and a cosmological constant, fits very well the measured data (see e.g.[12,18,29–45]).

The CMB is expected to be slightly polarized, since most of the CMB photons undergo a last Thomson scattering at recombination, and the radiation distribution around the scattering centers is slightly anisotropic. Any quadrupole anisotropy in the incoming distribution produces linear polarization in the scattered radiation. The main term of the local anisotropy due to density (scalar) fluctuations is dipole, while the quadrupole term is much smaller. For this reason the expected polarization is quite weak ([46–49]). The polarization field can be expanded into a curl-free component (E-modes) and a curl component (B-modes). Six auto and cross power spectra can be obtained from these components: $\langle TT\rangle$, $\langle TE\rangle$, $\langle EE\rangle$, $\langle BB\rangle$, $\langle TB\rangle$, and $\langle EB\rangle$. For example

$$c_\ell^{TE} = \langle TE\rangle = \langle a^T_{\ell,m} a^{E,*}_{\ell,m}\rangle \qquad (4)$$

where the $a^E_{\ell,m}$ and $a^B_{\ell,m}$ decompose the map of the Stokes parameters Q and U of linear polarization in spin-2 spherical harmonics:

$$(Q \pm iU)(\theta,\phi) = \sum_{\ell m} \left(a^E_{\ell m} \mp i a^B_{\ell m}\right) \ _{\pm 2}Y_{\ell m}(\theta,\phi) \tag{5}$$

.

Due to the parity properties of these components, standard cosmological models have $\langle TB \rangle = 0$ and $\langle EB \rangle = 0$. Linear scalar (density) perturbations can only produce E-modes of polarization (see e.g.[50]). In the concordance model, $\langle EE \rangle \sim 0.01 \langle TT \rangle$, making $\langle EE \rangle$ a very difficult observable to measure. The power spectrum c_ℓ^{EE} derived from the current best-fit cosmological model is plotted in fig.1 (top-left panel).

Tensor perturbations (gravitational waves) produce both E-modes and B-modes. If inflation happened (see e.g.[51–54]), it produced a weak background of gravitational waves. The resulting level of the B-modes depends on the energy scale of inflation, but is in general very weak (see e.g.[55,56]). Alternative scenarios, like the cyclic model,[57] do not produce B-modes at all.[58]

There is a strong interest in measuring CMB polarization, and in particular the B-modes, because their detection would represent the final confirmation of the inflation hypothesis, and their level would constrain the energy-scale of the inflation process, which, we know, happened at extremely high energies (which cannot be investigated on earth laboratories[59]).

For long time attempts to measure CMB polarization resulted in upper limits (see e.g.[60–65]). The possibility of detecting the $\langle BB \rangle$ signature of the inflationary gravity waves background renewed the interest in these measurements ([66–80]). The first statistically significant detections of CMB polarization have been reported by the coherent radiometer experiments DASI,[81] CAPMAP,[82] CBI,[83] WMAP for both $\langle TE \rangle$[77] and $\langle EE \rangle$,[84] and by the bolometric instrument BOOMERanG-03.[85–87] The quality of CMB polarization measurements has improved steadily with the introduction of instruments with detectors arrays, like QUAD,[88–90] BICEP,[91] and QUIET.[92]

Recent measurements of the angular power spectra of CMB polarization are collected in fig.3. The polarization power spectra measured by these experiments are all consistent with the forecast from the "concordance" model best fitting the WMAP $\langle TT \rangle$ power spectrum. In addition, they constrain the optical depth to reionization (the process ionizing the universe when the first massive stars formed), which is not well constrained by anisotropy measurements alone (see e.g.[93]).

The WMAP data have sufficient coverage to allow a stacking analysis and show the irrotational pattern of polarization pseudovectors around cold and hot spots of the CMB sky:[45] a clear visual demonstration of the polarization produced by density perturbations in the early universe.

To date, measurements of the rotational component of the polarization field $\langle BB \rangle$ resulted in upper limits, implying a ratio of tensor to scalar fluctuations $r \lesssim 0.3$.

2. OBSERVING THE CMB

The CMB is a diffuse mm-wave source, filling the sky (with a photon density of $\sim 400\gamma/cm^3$) and very faint with respect to radiation produced in the same wavelength range by our living environment and by the instruments used to measure it (the telescope, the optical system, the filters, the detector). The greatest difficulty in measuring the CMB is to reduce the contamination from other sources.

Measuring the specific brightness of the CMB with the COBE-FIRAS instrument required cooling cryogenically the spectrometer (a Martin-Puplett Fourier-Transform Spectrometer) and the bolometric detectors, and launching it in a 400 km orbit. The first operation reduced drastically the emission of the instrument and the noise of the detectors, the second minimized the emission of the earth atmosphere. The COBE-FIRAS was a null-instrument, comparing the specific sky brightness, collected by a multi-mode Winston concentrator,[94] to the brightness of an internal cryogenic blackbody reference. The output was precisely nulled (within detector noise) for T_{ref}=2.725 K . This implies that the brightness of the empty sky is a blackbody at the same temperature, and that the early universe was in thermal equilibrium. The brightness of a 2.725K blackbody[95] is relatively large (compared to the typical noise of mm-wave detectors), but everything at room temperature emits microwaves

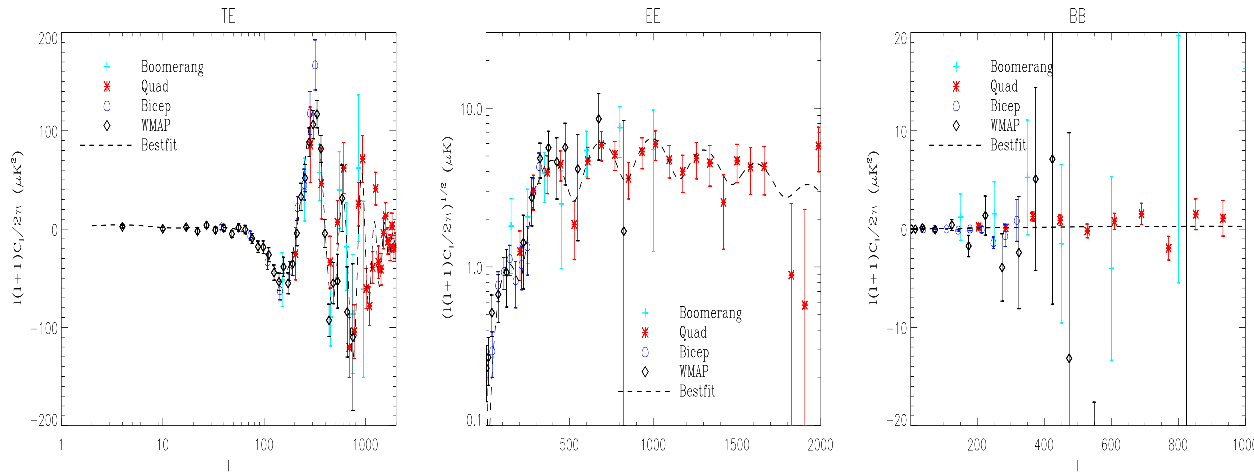

Figure 3. **Left:** Recent selected measurements of the angular cross-spectrum Temperature-E-modes-polarization $\langle TE \rangle$. **Center:** Recent selected measurements of the angular power spectrum of E-modes-polarization $\langle EE \rangle$. **Right:** Recent selected measurements (upper limits) of the angular power spectrum of B-modes-polarization $\langle BB \rangle$. Note the different vertical scales for the three plots. The dashed line is the model prediction for the same cosmological parameters best fitting $\langle TT \rangle$ measurements.

in the same frequency range: the instrument itself, the surrounding environment, the earth atmosphere. A room-temperature blackbody is orders of magnitude brighter than the CMB. Low emissivity, reflective surfaces must be used to shield the instrument, which needs to be cooled to cryogenic temperatures. Also, to avoid a very wide dynamic range, a cryogenic reference source should be used in the comparison. All this drove the design of the COBE-FIRAS instrument .[1]

The FIRAS one can be considered a definitive measurement of the spectrum of the CMB in the mm range: the deviations from a pure blackbody are less than 0.01% in the peak region, small enough to be fully convincing about the thermal nature of the CMB. However, there are regions of the spectrum where small deviations from a pure blackbody could be expected.

The ARCADE experiment,[96,97] another cryogenic flux collector working with coherent detectors from a stratospheric platform, focused on the low frequency end of the spectrum, looking for cm-wave deviations. In addition to emission from unresolved extragalactic sources, processes like the reionization due to the first stars, and particle decays in the early universe, would heat the diffuse matter, which in turn would cool, injecting the excess heat in the CMB (see e.g.[98]).

CMB anisotropy and polarization measurements target at much smaller brightnesses. The specific brightness of CMB anisotropy (and its polarization) is a modified blackbody

$$\Delta B = B(\nu, T_{CMB}) \frac{xe^x}{e^x - 1} \frac{\Delta T}{T} \quad ; \quad x = \frac{h\nu}{kT} \tag{6}$$

peaking at 220 GHz, and with $\Delta T/T$ of the order of 30 ppm, resulting in very faint brightness differences. However, in differential measurements common mode signals (coming from the average CMB but also from the instrument and the environment) can be rejected with high efficiency.

The focus here shifts on angular resolution (i.e. size of the telescope), sensitivity (i.e. noise of the detectors and photon-noise from the radiative background), and mapping speed.

2.1 Angular Resolution and Sidelobes

Theory predicts a power spectrum c_ℓ^{**} with important features at degree and sub-degree angular scales (i.e. multipoles above $\ell = 100$, see top panel of Fig.1). Resolving those features requires sub-degree angular resolution.

In the bottom panel of Fig.1 we plot the window function (i.e. the sensitivity of the instrument to different multipoles) for Gaussian beams with different $FWHM$: $B_\ell^2 = e^{-\ell(\ell+1/2)/\sigma^2}$, with $\sigma = FWHM/\sqrt{8\ln 2}$.[99]

At the frequency of maximum specific brightness of the CMB (160 GHz), and for a FWHM of 10′, the diameter of the entrance pupil of a diffraction-limited optical system has to be around 0.8 m. However, to reduce the spillover from strong sources in the sidelobes, it is needed to oversize the entrance pupil (i.e. the diameter of the collecting mirror/lens) leaving a guard-ring around the entrance pupil. The aperture stop is placed in a cold part of the system, effectively apodizing the illumination of primary light collector. So, at least meter-sized telescopes are needed to explore the features of the angular power spectrum of the CMB, while 10m class telescopes are needed to study its finest details.

Bolometric systems are capable of integrating many radiation modes, boosting their sensitivity at the cost of a corresponding increase in the size of the entrance pupil. At lower frequencies, where the atmosphere is more transparent, the required telescope size increases by a large factor (for example by a factor ~ 4 at ~ 40 GHz), entering in the realm of large and expensive telescope structures, including compact interferometric systems.

For all these reasons, CMB telescopes cannot easily be cooled at cryogenic temperatures to reduce their radiative background, unless they are operated in space (see below).

The control of telescope sidelobes is also extremely important. If ground pickup is not properly minimized, the nuisance signal coming from the earth emission in the far sidelobes can be comparable or larger than the CMB anisotropy signal. The detector will receive power from the boresight, pointed to the sky, but also from all the surrounding sources, weighted by the angular response R as follows:

$$W(\theta,\phi) = A\int_{4\pi} B(\theta',\phi')R(\theta-\theta',\phi-\phi')d\Omega \tag{7}$$

where $B(\theta,\phi)$ is the brightness from direction (θ,ϕ).

Beyond the main beam (off-axis angles $\theta \gg \lambda/D$) the envelope of the angular response R for a circular aperture in diffraction limited conditions scales as θ^{-3}. For a ground based experiment, where the sky fills the main beam with solid angle $\Omega_M \ll 1$ sr and the emission from ground fills a large solid angle in the sidelobes $\Omega_S \sim 2\pi$ sr, the detected signal can be approximated as

$$W \simeq A\left[B_{sky}\langle R\rangle_M\Omega_M + B_{ground}\langle R\rangle_S\Omega_S\right] = A\left[I_M + I_S\right] \tag{8}$$

where $\langle\rangle_{M,S}$ represent the averages of the angular response R over the main lobe (where $\langle R\rangle_M \lesssim 1$) and over the sidelobes (where $\langle R\rangle_S \ll 1$). In the case of a 2.725K sky emission and of a 250K ground emission, for example, in order to have $I_S \ll I_M$ we need $\langle R\rangle_S \ll 4\times10^{-5}$ for a 10^o FWHM experiment, and $\langle R\rangle_S \ll 1\times10^{-8}$ for a 10′ FWHM experiment. Hence the necessity of additional shields surrounding the telescope, to increase the number of diffractions that radiation from the ground must undergo before reaching the detectors.

The situation is even worse in the case of anisotropy measurements, where the interesing signal is of a few μK. Here a differential instrument is needed, which helps in reducing the sidelobes contribution to the measured signal. The last resource is to send the instrument far from the earth, so that the solid angle occupied by ground emission is $\ll 2\pi$. This is the case for the WMAP and Planck space missions, devoted to CMB anisotropy and polarization measurements. They both operate from the Lagrange point L2 of the sun-earth system, where the solid angle occupied by the earth is only 2×10^{-4} sr. This relaxes the conditions on sidelobes rejection by a factor ~ 30000 with respect to ground-based or balloon-borne experiments.

The telescope and shields configurations are optimized using numerical methods (see e.g. www.ticra.com), normally based on the geometrical theory of diffraction[100] to speed-up the computations (see e.g.[101]).

To reduce the sidelobes, off-axis telescope designs are preferred, and complemented by extensive ground and sun shields (see e.g.[85, 102–110]). In particular, compact test range telescope configurations offer wide focal planes (allowing the use of large format detector arrays, see below), with excellent cross-polarization quality (which is essential for CMB polarization studies) see e.g.[111, 112]

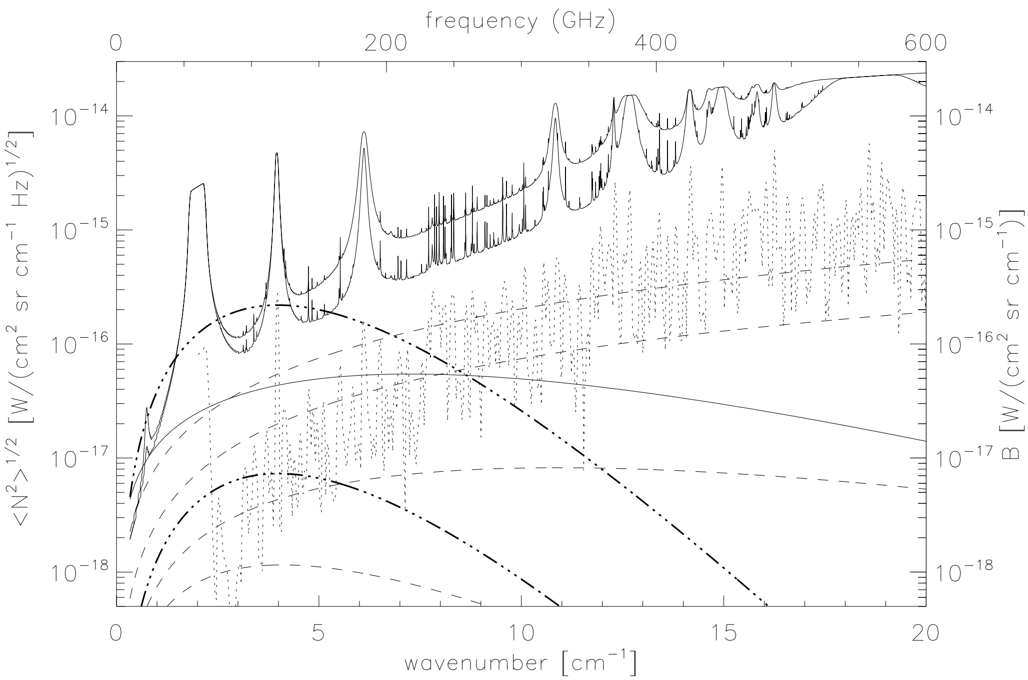

Figure 4. Photon noise from the natural radiative background and from the instrument (left scale) compared to CMB anisotropy and polarization signals (right scale). The two top continuous lines represent the noise due to quantum fluctuations of atmospheric emission, for 2 mm PWV and 0.5 mm PWV, typical of a high altitude ground based observatory. The dotted line is the noise due to quantum fluctuations of the emission from the residual atmosphere, at balloon (41 km) altitude. The lower thin continuous line is the photon noise of the CMB itself. The dashed lines represent the noise produced by a low-emissivity ($\epsilon = 5 \times 10^{-3}$) optical system at different temperatures (300K, 40K, 4K, 1.5K from top to bottom). The dot-dashed lines represent a typical CMB anisotropy brightness fluctuation (corresponding to $\Delta T_{CMB} = 90\mu K$, higher line) and a typical CMB polarization fluctuation (corresponding to $\Delta T_{CMB} = 3\mu K$, lower line).

The actual sidelobes pattern is usually measured with strong far-field sources (like a Gunn oscillator in the focus of a large telescope, producing a plane-wave to illuminate the telescope of the instrument). For space missions, where the operating environment can be very different from the laboratory conditions, the sidelobes are measured during the mission, using the Moon or the Sun (see e.g.[113]).

2.2 Sensitivity

The sensitivity of a detector measuring CMB anisotropy depends on detector performance (usually quantified by its intrinsic noise equivalent temperature, NET_i, in CMB temperature fluctuation units (μK_{CMB})) and on the noise of the incoming radiative background, NET_γ. The latter is computed following[114] (but see also[115,116]): it depends on the emission of the instrument itself (presence of warm lenses, mirrors, windows) and on the atmosphere above the operation site (the telescope can be ground-based, on a stratospheric balloon, or on a satellite). Operating above the earth atmosphere photon noise is reduced, and the instrument must be cooled cryogenically to exploit the optimal environmental conditions. In figure 4 we compare the photon noise from the natural radiative background and from the instrument to the signal to be detected, for several typical situations. Keep in mind that photon noise $\langle N^2 \rangle^{1/2}$ in figure 4 is given for unit optical bandwidth (1 cm^{-1}), unit electrical bandwidth (1 Hz, roughly corresponding to 1 s of integration), and for a throughput $A\Omega = 1cm^2sr$, and scales as the square root of these; moreover, in Rayleigh-Jeans conditions, it scales also as the square root of the emissivity ϵ.

From figure 4 it is evident that ground-based observations are limited to low frequencies ($\lesssim$ 40 GHz) and the W and D bands (note, however, that only quantum fluctuations have been plotted here, while turbulence, winds, instabilities can increase atmospheric noise significantly). Balloon-borne telescopes can work with room-temperature telescopes, while to exploit the low radiative background of space the telescope should be cooled to at least 40K, and better below 4K if high frequency measurements are planned.

Quite recently mm-wave bolometers operated below 0.3K have achieved background limited conditions (i.e. $NET_i \lesssim NET_\gamma$). This is the case of the bolometers of the HFI instrument[117] aboard of the Planck satellite, where the telescope is cooled radiatively to 40K.[118] For these detectors $NEP_i \lesssim 10^{-17} W/\sqrt{Hz}$ ([119]), and a cold optical system is required, to exploit their excellent performance (compare this NEP_i to the photon noise in fig. 4, for a typical throughput $A\Omega \sim \lambda^2 \sim 0.05 cm^2 sr$).

2.3 Mapping Speed

Once background-limited conditions are reached, the only way to improve the performance of a CMB survey is to increase the number of detectors simultaneously scanning different directions, i.e. to produce large arrays of mm-wave detectors. This will boost the mapping speed of the experiment, by a factor of the order of the number of detectors in the focal plane. The need for large arrays required an important technology development to achieve fully automated production of a large number of pixels. This is very difficult to achieve in the case of coherent detectors, because of the cost and the power dissipation of each amplifier. In the case of bolometers and other incoherent detectors (like KIDs and CEBs, see below), it has been possible to devise pixel architectures which can be completely produced by photolithography and micromachining, with low cost and negligible power per pixel.

Bolometers are thermal detectors, absorbing radiation and sensing the resulting temperature increase. For a review of CMB bolometers development and operation see e.g.[120,121] The development of fully lithographed arrays is the result of a long process started with the development of the so-called spider-web bolometer,[122] followed by the polarization sensitive bolometer (PSB).[123] Several of these devices were arranged on the same wafer.[124] Then voltage-biased Transition Edge superconducting Sensors (TES) were developed (see e.g.[125–129] and integrated on the array wafer (see e.g.[130–137]). In parallel to the development of the TES bolometers, a large effort has been spent in the development of the readout electronics, which uses SQUIDs to read and multiplex a large number of detectors with a limited number of wires, thus maintaining the heat load on the cryostat at manageable levels.[138,139] These detectors have been installed at large CMB telescopes (ACT, SPT, APEX ...) with excellent performance, providing high resolution CMB measurements. Antenna coupling to the radiation, dual polarization sensitivity, and even spectral filtering are now also integrated in the TES wafers (see e.g.[140–146]), producing powerful imaging/polarimetry/spectrometry capabilities in a lightweight block.

In addition to TESs, the quest for large mm-wave cameras for CMB research drove the development of other non-coherent detection technologies.

In the MKIDs (microwave kinetic inductance detectors) low energy photons (like CMB photons, in the meV range) break Cooper pairs in a superconducting film, changing its surface impedance, and in particular the kinetic inductance L_k. The change is small, but can be measured using the film as the inductor in a superconducting resonator, which can have very high merit factor Q, up to $\simeq 10^6$, and thus be very sensitive to the variations of its components. Many independent MKIDs are arranged in an array, an shunt the same line, where a comb of frequencies fitting the resonances of the pixels is carried. CMB photons absorbed by a given pixel produce a change in the transmission of a single frequency of the comb. So MKIDs are intrinsically multiplexable, requiring only two shielded cables to supply and read hundreds of pixels. The initial KID concept,[147] where mm-wave photons are antenna coupled to the resonator, has evolved in the LEKID (Lumped Elements Kinetic Inductance Detector) concept,[148,149] where the resonator is shaped as an efficient absorber of mm-waves analogous to bolometer absorbers. The great advantage of MKIDs with respect to TES is that the fabrication process is significantly simpler, and also the readout electronics requires only a wide-band amplifier cryogenically cooled. Today, MKID arrays are produced in many laboratories (see e.g.[150–152]) and are starting to be operated at large telescopes (see e.g.[153,154]).

In a Cold Electron Bolometer (CEB)[155] the signal power collected by an antenna is capacitively coupled to a tunnel-junction (SIN) sensor and is dissipated in the electrons which act as a nanoabsorber; it is also removed from the absorber in the form of hot electrons by the same SIN junctions. This electron cooling provides

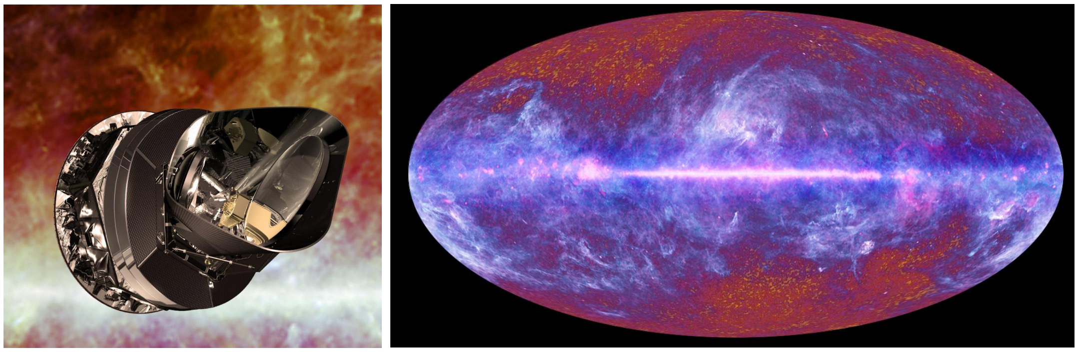

Figure 5. **Left:** The Planck satellite, scanning the sky in the mm/submm from the Lagrangian point L2 of the sun-earth system. **Right:** Map of the sky in Galactic coordinates, obtained from the full sky surveys of Planck at nine frequencies. The maps have been linearly combined in two ways: the red-yellow palette evident at high galactic latitudes is the combination maximizing CMB signals. Here the horizon-sized spots are ubiquitous and dominant at high galactic latitudes. The blue-white palette is the combination maximizing the local foreground. The power of wide frequency coverage is evident: from this map it is possible to monitor the faintest interstellar clouds at high galactic latitudes. Figure credit: European Space Agency.

strong negative electrothermal feedback, improving the time-constant, the responsivity and the NEP.[156] Since the thermistor is the gas of electrons, confined in a ~ 100 nm junction and thermally insulated from the rest of the sensor, these detectors should be quite immune to cosmic-rays hits, an important nuisance for TES and KIDs in space. Moreover, these detectors promise very good performance in a wide range of radiative backgrounds, while efficient multiplexing schemes are still to be developed.

3. CURRENT TRENDS IN CMB RESEARCH

We have entered the era of precision observations of the CMB.

Planck[157] has produced a shallow survey of the whole sky in nine mm - submm bands (centered at 30, 44, 70, 100, 143, 217, 353, 545, 857 GHz). Taking advantage of the wide frequency coverage and of the extreme sensitivity of the measurements, it is possible to separate efficiently the different contributions to the brightness of the sky along each line of sight (see figure 5).

While it is evident from fig.5 that foreground emission can be important even at high galactic latitudes, it is also clear that the multifrequency survey of Planck allows to detect and remove tiny contaminations from thin interstellar clouds. With the foregrounds under control, Planck is expected to produce very precise measurements of CMB anisotropy and polarization in the next data release, early in 2013.

High-resolution anisotropy measurements are now performed mainly in the direction of clusters of galaxies (SZ effect) and to search for non-Gaussianity of the CMB. High sensitivity polarization measurements aim at measuring B-modes from inflation and from lensing of E-modes. We will outline here a few, selected issues that we consider relevant for the continuation of these studies.

3.1 Sunyaev-Zeldovich Effect and spectral anisotropy measurements

The Sunyaev-Zeldovich (SZ) effect[158] is the energization of CMB photons crossing clusters of galaxies, due to the inverse Compton effect with the hot intergalactic plasma. The order of magnitude of the effect can be estimated noticing that the optical depth for a rich cluster is $\tau \sim n_e \sigma_T \ell \lesssim 0.01$ and the fractional energy gain of each interacting photon is of the order of $kT_e/m_e c^2 \sim 0.01$, so the fractional CMB temperature change will be $\Delta T/T \sim \tau k T_e/m_e c^2 \lesssim 10^{-4}$: a large signal if compared to the primordial CMB anisotropy. The SZ effect is thus a powerful tool for studying the physics of clusters and using them as cosmological probes (see e.g.[159–161]). Large mm-wave telescopes ([109, 110, 136]), coupled to imaging multi-band arrays of bolometers, are now operating in excellent sites and produce a number of detections and maps of the SZ effect in selected sky areas, discovering new clusters, and establishing cluster and cosmological parameters.

From the Planck data an early catalogue of massive clusters detected via the SZ effect has been extracted.[162] This consists of 169 known clusters, plus 20 new discoveries, including exceptional members.[163] All these measurements take advantage of the extreme sensitivity of bolometers, with their excellent performance in the frequency range 90-600 GHz where the spectral signatures of the SZ effect lie.

Several components contribute to the signal detected from the line of sight crossing the cluster: a thermal component due to the inverse Compton effect; a Doppler component, caused by the collective motion of the cluster with respect to the CMB restframe; a non-thermal component caused by a non-thermal population of electrons, produced by e.g. the AGNs present in the cluster, relativistic plasma in cluster cavities, shock acceleration; the intrinsic anisotropy of the CMB; the emission of dust, free-free and synchrotron in our Galaxy and in the galaxies of the cluster. Since the spectrum of thermal SZ significantly departs from the spectra of the foreground and background components, multi-frequency SZ measurements allow the estimation of several physical parameters of the cluster, provided there are more observation bands than parameters to be determined, or some of the contributions are known to be negligible. In[164] we have analyzed how different experimental configurations perform in this particular components separation exercise. Ground-based few-band photometers cannot provide enough information to separate all physical components, because atmospheric noise limits the number of useful independent bands. These instruments need external information (optical, X-ray, far-IR, etc.) to produce mainly measurements of the optical depth of the thermal SZ (see e.g.[165–172]).

Future space-based spectrometers can cover the full range of interesting frequencies and offer much more information. A cryogenic differential imaging Fourier Transform Spectrometer (FTS) in the focal plane of a space mission with a cold telescope, like Millimetron,[173] would be a powerful experiment, measuring accurately all the parameters of a cluster. The FIRAS experiment has demonstrated the power of these large-throughput, wide frequency coverage instruments, which are intrinsically differential. In that case one of the two input ports collected radiation from the sky, while the other port was illuminated by an internal blackbody: the perfect nulling of the measured difference spectrum demonstrated accurately the blackbody nature of the cosmic microwave background. In this implementation, the two input ports of the instrument collect radiation from two contiguous regions of the focal plane of the same telescope (see left panel of fig.6). In this way only the anisotropic component of the brightness distribution produces a measurable signal, while the common-mode signals from the instrument, the telescope, and the CMB itself are efficiently rejected. The FTS is sensitive to a wide frequency band (say 70 - 1000 GHz for SZ studies), so photon noise is the limiting factor. In fig.6 we compare what can be achieved with a warm system on a stratospheric balloon[174–176] (center panel) to what can be ultimately achieved with a cold system in deep space[164] (right panel). In both cases important improvements with respect to the state-of-the-art determination of cluster parameters are expected. The intermediate case of a cold spectrometer coupled to a warm telescope in a Molniya orbit has been studied in[177] .

Other important scientific targets of these instruments are the measurement of the C^+ and CO lines, in the redshift desert and beyond, for a large number of galaxies, and spectral observations of a number of processes in the early universe and in the recombination and reionization eras (see e.g.[177, 179–183]).

3.2 B-modes of CMB polarization

Measuring the tiny B-modes signal is a formidable experimental challenge. For this reason it is very important that independent teams develop advanced experiments, using different techniques and methods. Only independent consistent detections will provide convincing evidence for the existence of B-modes.

The mainstream in this field is the use of large arrays of single-mode bolometric polarimeters, using a polarization modulator in the optical path (as close as possible to the input port of the instrument, to avoid modulating instrumental polarization) to modulate only the polarized part of the incoming signal. The throughput of the telescope has to be very large, of the order of $\sum_{i=1}^{n} N_i \lambda_i^2 / F_i$, where the number of detectors N_i in each band i is of the order of 10^3, and the filling factor of the focal plane is $F_i \lesssim 1$.

The removal of the polarized foreground (mainly produced by the interstellar medium) is a matter of the utmost importance. It has been analyzed in great detail, most recently in the framework of the Planck mission (see e.g.[184–186] and references therein) and of future missions devoted to CMB polarization (see e.g.[187]). The solution is to carry out surveys with wide frequency coverage, from tens of GHz (to survey strongly polarized

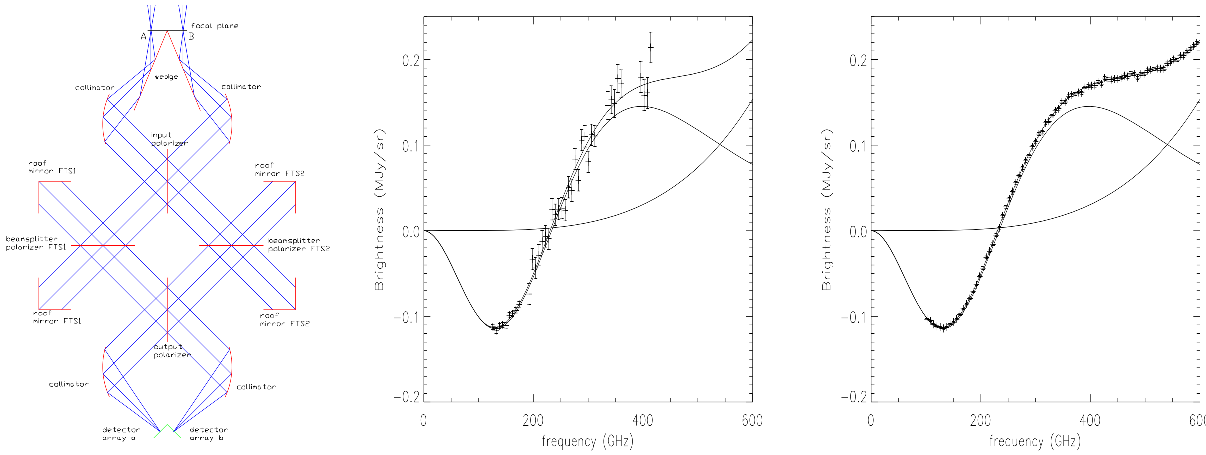

Figure 6. **Left** : Block-diagram of a differential FTS. This very symmetrical configuration reduces instrumental offsets and doubles the efficiency with respect to the standard MPI FTS.[178] **Center** : Simulated observations of a rich cluster of galaxies with a warm differential FTS aboard of a stratospheric balloon, like OLIMPO. **Right** : Same for a differential FTS aboard of a satellite in L2, with a large (10m) cold (4K) telescope, like Millimetron. In both cases, 3 hours of observation are assumed, and bolometer performance limited only by the radiative background. The two continuous lines represent the SZ effect from the plasma in the cluster and differential emission of interstellar dust, the two main components of the measured brightness.

synchrotron emission) to several hundreds of GHz (to survey polarized emission from interstellar dust). For this reason a number of bands $n \sim 10$ is required to separate the foreground components from the primordial CMB signal. Accommodating all the bands in the focal plane of the telescope exacerbates the large throughput problem for these systems, also because only the center region of the focal plane has optimal polarization efficiency and beam-symmetry properties. Multichroic pixels including bolometric detectors in 3 or more bands under the same microlens have been developed,[146] allowing a very efficient use of focal plane space. This approach has been proposed for the LiteBIRD satellite.[188]

In the case of incoherent detectors, intrinsically insensitive to the polarization status of the incoming power, the classic Stokes polarimeter requires a half-wave plate retarder plus a polarizer. If the HWP is rotated with a rotation rate $\dot{\theta}$, the linearly polarized part of the incoming signal is modulated at $4\dot{\theta}$, while the unpolarized and the circular polarization components are not modulated. Wide-band retarders can be obtained in transmission using a sandwich of birefringent crystals (see e.g.[189–193]) or suitable meta-materials assembled with metal meshes.[194] In reflection, a rotation mirror / polarizer combination[195] can be used, or a translating polarizer / mirror assembly (Variable Delay Modulator[196]), or a translating circular polarizer / mirror combination (Transational Polarization Rotator[197]). The main issues with these modulators is the equalization of the transmission (reflection) for the two orthogonal polarizations (any mismatch, even at a level of 1%, will produce a comparatively very large $2\dot{\theta}$ signal) and the need to cool at cryogenic temperatures the modulator, to reduce its (polarized) emission (see[198] for a discussion).

Reaching satisfactory performance over a wide frequency band and a wide throughput is problematic. In the case of the dielectric HWP, a sandwich of differently oriented plates is required, following the Pancharatman[199] recipe. This approach is suitable for accurate measurements of CMB polarization in the range 120-450 GHz.[200] However, it is currently impossible to obtain large-diameter ($\gtrsim 30cm$) slabs of sapphire (or any other birefringent crystal suitable for mm wavelengths), so their use is limited to medium throughput systems. Using metal meshes might solve the problem, but requires a careful equalization of the conductivity of the meshes. In the case of the mirror/polarizer combination, which can be produced in very large sizes, the operative band is restricted to $\sim 20\%$ of the center frequency. It is possible, however, to operate the modulator at multiples of a fundamental frequency, with decreasing fractional bandwidth, as proposed in.[201]

A Martin-Puplett Fourier Transform Spectrometer,[178] with the two input ports A and B (fig.6) co-aligned to look at the same sky patch, becomes a polarimeter. In fact, it produces at the two output ports a and b, with polarization x and y, the following 4 signals, which can be detected by 4 independent detectors: $[I_{a,x}(z) - \langle I_{a,x}\rangle] \propto \int(E^2_{B,x}(\sigma) - E^2_{A,y}(\sigma))cos(4\pi\sigma z)d\sigma$; $[I_{a,y}(z) - \langle I_{a,y}\rangle] \propto \int(E^2_{B,y}(\sigma) - E^2_{A,x}(\sigma))cos(4\pi\sigma z)d\sigma$; $[I_{b,x}(z) - \langle I_{b,x}\rangle] \propto \int(E^2_{A,x}(\sigma) - E^2_{B,y}(\sigma))cos(4\pi\sigma z)d\sigma$; $[I_{b,y}(z) - \langle I_{b,y}\rangle] \propto \int(E^2_{A,y}(\sigma) - E^2_{B,x}(\sigma))cos(4\pi\sigma z)d\sigma$, where σ is the wavenumber and z is the position of the moving mirror. Summing and subtracting the Fourier-transformed signals from detectors couples it is possible to estimate the *frequency spectra* of the Stokes parameters of the incoming radiation. This is the principle of operation of the proposed PIXIE experiment,[182] a space-based large-throughput spectro-polarimeter covering the frequency range 30-6000 GHz. The optical axis of the spectro-polarimeter is aligned to the spin axis of the satellite, so that any polarization signal becomes spin-synchronous. In this configuration, the specifications for beam ellipticity, and beam, gain and polarization mismatch for the four detectors are very stringent. These could be relaxed with the use of a rotating achromatic HWP at the entrance of the system, but it is currently impossible to fabricate a high-efficiency highly-balanced HWP over such a wide frequency range.

There is a long list of potential systematic effects in Stokes polarimeters (see e.g.[202]), and the requirements for a clean detection of B-modes are extremely stringent (see e.g. table 6.1 in[203]). A few examples: tens of mK signals at $2\dot{\theta}$ are produced by the unpolarized 2.7K background, modulated by $\sim 1\%$ efficiency mismatch between the ordinary and extraordinary rays in the waveplate. The emission of a mismatched HWP also produces tens of mK signals at $2\dot{\theta}$, unless its temperature is below 2K. These signals challenge the dynamic range of the detector, which is optimized for measuring CMB polarization signals $\sim 10^4$ times smaller. Any non-linearity in the detector can convert part of this $2\dot{\theta}$ signal into a $4\dot{\theta}$ signal, producing a large offset in the polarization measurement. If part of the emission of the polarizer is reflected back by the waveplate, it is modulated at $4\dot{\theta}$, contributing with additional $\sim$ few μK signals to the offset. A possible solution to this problem is the step and integrate strategy (see e.g.[204]). At variance with the continuous rotation strategy, here the HWP is kept steady during sky scans, and angular steps are performed at the turnarounds. All the systematic effects generated internally to the instrument produce a constant offset during each scan, which can be removed, while the sky polarization is modulated at the (very low) frequency of the repetition of the scans. In addition to these effect, other noticeable sources of systematic problems are the ellipticity of the main beam ($< 10^{-4}$), the level of its polarized sidelobes ($< 10^{-6}$), the instrumental polarization ($< 10^{-4}$), the relative gain calibration ($< 10^{-5}$): all these convert unpolarized brightness fluctuations into apparent B-modes signals; an error in the main polarimeter axis angle ($< 0.2^o$) and the cross-polar response ($< 3 \times 10^{-3}$) convert E-modes into apparent B-modes; moreover, the relative pointing of differenced observation directions must be < 0.1 arcsec to avoid conversion of brightness fluctuations into apparent B-mode signals. Pathfinder experiments are the best way to find and test the best mitigation methods for all these subtle systematic effects. Current attempts exploit different techniques, ranging from ground-based coherent polarimeters, like QUIET,[92] to ground-based bolometer arrays with HWP, like POLARBEAR,[205] to ground-based bolometric interferometers, like QUBIC,[206] to stratospheric balloons like SPIDER,[207] EBEX,[208] and LSPE.[209] Using completely independent techniques, these experiments provide a powerful test set for any detection of B-modes in the CMB, in view of a post-Planck next generation space mission for the CMB.

4. CONCLUSIONS

The future of CMB studies is bright. A large community has grown around the success of CMB missions, producing large amounts of excellent data. The experiments have drifted from a situation where sensitivity was the issue to a situation where control of systematic effects is the main problem. So we are facing very difficult challenges, with the ambition of understanding the most distant phenomena happening in our universe, analyzing tiny signals embedded in an overwhelming noisy background. When we approached CMB research for the first time, in 1980, measuring the intrinsic anisotropy of the CMB was considered almost science-fiction. Today CMB anisotropy is measured in a single pass with scanning telescopes using large arrays of bolometers. This experience makes us confident that much more is coming in this field, with the enthusiastic contribution of young researchers and the cross-fertilization between cosmologists, astrophysicists, solid-state / detector physicists, optics experts.

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