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Measuring polarization of interstellar dust: a modulator for the PILOT experiment

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Abstract. Precise measurements of the Cosmic Microwave Background Polarization (CMBP) require improved knowledge of its foregrounds, in order to remove them from the cosmological signal. Among the foregrounds, the polarization from interstellar dust dominates at frequencies higher than 100 GHz. One way to measure the linear polarization of interstellar dust requires a rotating Half Wave Plate (HWP), at cryogenic temperatures, followed by a fixed polarizer. We present the design of a cryogenic polarization modulator in which the rotation of the cold birefringent crystal is driven by a DC motor running at room temperature, and the control of its position is assured by a system of optical fibers. The modulator is optimized to be implemented in PILOT, a stratospheric balloon which in the near future will study the interstellar medium in two bands around 545 and 1250 GHz. Mechanical, optical and cryogenic tests are also discussed.

Key words. Astrophysics: interstellar dust – Cosmology: Cosmic Microwave Background – Cosmology: foregrounds – Cryogenics: mechanics – Cryogenics: thermal loads – Polarization: half wave plate – Polarization: modulation

1. Introduction

The Cosmic Microwave Background (CMB), originated from the decoupling between electrons and photons has a black body spectrum with a temperature of $(2.728 \pm 0.004)\,K$ (Fixsen et al. 1996). Sensitive measurements of the anisotropy of the CMB, accurately performed e.g. by the BOOMERanG balloon (de Bernardis et al. 2000) and the WMAP satellite (Hinshaw et al. 2007), have revealed the flat geometry of the universe at large scales. They support a primordial inflationary period and a present-day universe made up of 5% baryonic matter, 30% cold dark matter and for the remaining 65% by dark energy (Ruhl et al. 2003).

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The in CMB observations challenge is the detection of the linear polarization of the CMB, produced by Thomson scattering at the decoupling (Lin & Wandelt 2006). We expect a linear polarization pattern on the sky with both scalar and tensor components. The former produces the electric modes (hereafter E modes), the latter, coming from gravitational waves, both E and magnetic (B) modes in similar amount (Hu & White 1997). The E modes power spectrum will have typical values around 1% of the temperature one: about few μK rms. For the C_l^{BB} spectrum, we expect a typical amplitude lower than 10^{-4} of the C_l^{TT} spectrum. A possible detection of the B modes, in fact, would confirm the inflationary theory (Kamionkowski et al. 1997). Measurements performed with the DASI (Kovac et al. 2002) (Leitch et al. 2004), WMAP (Page et al. 2003) and BOOMERanG (Piacentini et al. 2006) (Montroy et al. 2006) experiments, confirmed the polarized signature of the CMB (MacTavish et al. 2006); nevertheless the detection is still at a level of few σ in the best cases. Different sources, called foregrounds, are present between the CMB and the observer, and emit polarized radiation at the same frequency of the CMB (Baccigalupi et al. 2001) (Baccigalupi et al. 2001) (Hanany & Rosenkranz 2003). Foregrounds dominate over the E (B) modes of the CMB in distinct ranges of spatial l and spectral ν frequencies (Tucci et al. 2005). From optical surveys (Fosalba et al. 2002) (Heiles 2000) we know that aspherical interstellar dust grains, aligned by the galactic magnetic field through the Davis-Greenstein paramagnetic relaxation (Evans 1993) (Lazarian & Cho 2003) or by radiative torques (Dolginov 1972) (Dolginov & Mytrophanov 1976), polarize starlight, by differential absorption. This implies a polarized emission both in the Galactic plane and at high latitudes, with a degree of polarization which is frequency dependent (Martin 2007). The result is a foreground dominating over CMBP at frequencies larger than $100\,GHz$. Detection of linearly polarized radiation requires a HWP, rotating at frequency f_0, coupled to a fixed wire grid polarization analyzer. The output signal is sinusoidally modulated at frequency $4f_0$, with an amplitude of modulation polarization dependent. The frequency of modulation should be chosen to be far from the $1/f$ noise region of the detector and any spurious signal and\or systematic effect. Different CMBP experiments have developed distinct implementations of this advantageous technique (Hanany et al. 2003) (Johnson et al. 2003) (Masi et al. 2005) and others are under study (Oxley et al. 2004).

2. The PILOT experiment

2.1. The science goal

The science goal of PILOT is the measurement of the polarization of the continuum emission in the diffuse interstellar medium (ISM) at frequencies around 545 and $1250\,GHz$, with a resolution of $3.29'$ and $1.44'$ respectively (Bernard et al. 2007a) (Bernard et al. 2007b). The NEP for the first (second) channel will be equal to $2.9 \cdot 10^{-16}\,(3.9 \cdot 10^{-16}) W/\sqrt{Hz}$. PILOT will study the large scale distribution of the galactic magnetic field and the alignment properties of the dust grains. These observations will allow to understand the role played by the magnetic field in the gravitational collapse leading to the formation of new stars and in the molecular clouds. For the first time the dust polarized emission will be studied in the diffuse regions of the ISM (Dupac et al. 2003). PILOT observations will provide strong constraints for the dust models, in particular via the dependence on frequency from the degree of polarization.

2.2. The hardware

The Archeops balloon experiment has measured interstellar dust polarization in few regions in the Galactic plane, but at high latitudes we have only upper limits (Benoit et al. 2004).

PILOT is a stratospheric balloon (about $37\,km$ height), provided with a $0.7\,m$ primary Gregorian telescope. The dust emission, phase shifted by a rotating HWP and divided in the two orthogonal components of polarization, by a fixed polarizer, is detected by 2048 sensitive bolometric detectors, cooled at 0.3 K by a closed cycle ^{3}He fridge. Detectors arrays are necessary to obtain wide and accurate maps of interstellar dust and of its polarization. The reimaging optical system is cryogenically cooled to reduce its thermal emission. PILOT will map the sky with scans at constant elevation, reducing the residual atmospheric contribution, in an azimuth range of ±30°, with elevation between 20° and 60°. With this scanning strategy PILOT will be able to carry out a *large survey* (along the Galactic plane, with long scans, about 30° in size, and a typical mapping speed of 300 square degrees per hour) and a *deep field survey* (for the diffuse regions at high Galactic latitudes, with small scans, 3° in size, at a mapping speed of 9 square degrees per hour).

3. The necessity of cryogenic temperatures

The non ideal behavior of the HWP, polarizer and detector changes the amplitude and the offset of the astrophysical signal. We have studied the features that a polarimeter must have to maximize its efficiency, vs the operation temperature of the analyzer components. The detected signal vs rotation angle of the waveplate is in general a sinewave. For such a sinewave, with amplitude A and offset O, we define two non-ideality parameters: $Amplitude = |\frac{A_{real}}{A_{ideal}} - 1|$ and $Offset = |\frac{O_{real}}{O_{ideal}} - 1|$, where $A_{real\,(ideal)}$ is the amplitude of the real (ideal) signal and $O_{real\,(ideal)}$ the offset. Both the non-ideality parameters defined above should be << 1.

We have simulated the polarized emission from interstellar dust detected by this kind of polarimeter, for distinct temperatures of the HWP and of the polarizer, and estimated the non-ideality parameters. The source, at $30\,K$ and with emissivity of the order of 10^{-3}, emits radiation, horizontally polarized with a degree of polarization of 5 %, centered at the two PILOT wavelengths, $240\,\mu m$ and $550\,\mu m$, in a band $\Delta\lambda = 10\%\,\lambda$. The astrophysical radiation crosses a rotating HWP, with absorbing coefficients $a_x = a_y = 0.99$ and emissivity 0.1, followed by a horizontal polarizer with $p_x = 0.99$, $p_y = 0.01$ and emissivity 0.01. It is detected by a bolometer, with emissivity 0.5, cooled at 0.3 K. The incoming radiation has an incident angle, with respect to the normal to the HWP, equal to 1°. Multiple reflections between devices are properly taken into account.

We need to cool down to cryogenic temperatures the polarizer and the HWP to increase the efficiency of the polarimeter. Only the radiation of the polarizer reflected by the HWP, produces a signal with a $\cos 4\theta$-law. When both the polarizer and the HWP are cooled down to 2 K and 4 K, respectively, we get, for both channels, $Amplitude = 0.13$ and $Offset = 26.51$. To reach an $Offset = 0.36$ we should cool down the polarizer and the HWP to 0.5 K and 1.4 K, respectively. The $Offset$ parameter decreases rapidly with T_{HWP} and more slowly with T_{Pol}.

Since the bolometers are cooled down to $0.3\,K$ to get a typical NEP of about $10^{-16} W/\sqrt{Hz}$, this makes possible to neglect the radiation emitted by the detector, transmitted by the polarizer and reflected backwards by the HWP. This radiation would produce a problematic signal with a $\cos 4\theta$-law if the detector itself wasn't cooled at cryogenic temperatures.

4. The cryogenic polarization modulator

4.1. The experimental requirements

The HWP will be rotated in eight positions, separated by 11.25°, for a total angular range of 78.75°, with a typical angular speed of about 0.19 *rpm*. With this strategy, when bolometers detect radiation, nothing is rotating and we don't introduce microphonic signals that could be produced by continuously rotating mechanisms. In this way we measure the linear polarization of the interstellar dust with a sufficient angle redundancy, without waiting for the sky rotation. The relative accuracy in the position of the HWP should be less than 1° to reduce the errors in the polarization degree and angle. With the rotation of the HWP performed at cryogenic temperatures $(4 \div 10)K$, only a power load of few mW is tolerable on

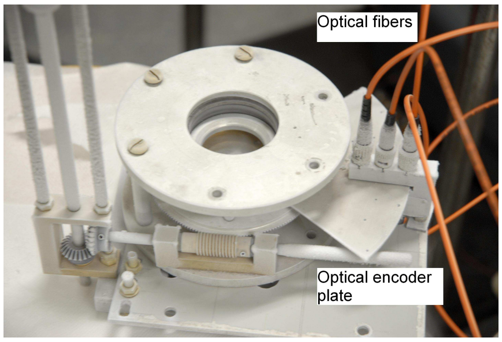

Fig. 1. The PILOT cryogenic polarization modulator after a test in liquid nitrogen.

the Helium tank: this makes impossible using commercial cryogenic stepping motors. The cryogenic temperatures also makes difficult the continuous knowledge of the HWP position.

4.2. Description of the hardware

A DC micromotor, at room temperature, rotates the HWP, transmitting the motion by means of a long fiberglass drive shaft, a couple of bevel gears and a gear wheel. Two pairs of de-greased single direction thrust ball bearings compensate the substantial shrinking of all parts when the system is cooled down at cryogenic temperatures. The position control of the HWP is assured by a system exploiting three pairs of optical fibers. A rigid plate, revolving together with the HWP, the *optical encoder plate*, is provided with holes which reproduce, in binary code, the eight predetermined positions (Fig. 1). The presence of these holes is read through the optical fibers. From the succession of null and high signals, we can reconstruct the HWP position. A microcontroller manages the electronic signal and the mechanical action: in this way the HWP rotation is driven in a completely automated way.

5. Tests

5.1. Angular speed of rotation

The angular speed of the HWP rotation has a linear trend with the voltage supply of the control system. To revolve the HWP from one position to the following the control system has to be supplied with a voltage greater than\equal to 16 V.

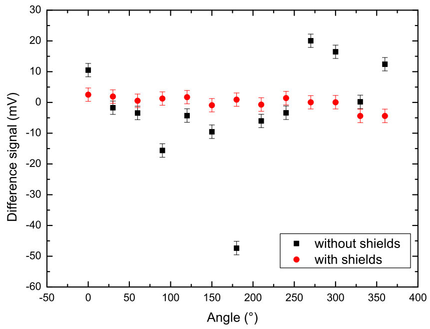

Fig. 2. Spurious modulation of the modulator; to each measure the mean signal when the shields are inside the modulator has been subtracted.

Table 1. Relative accuracy of the HWP position (0°). The second column is the mean deviation angle, the third the standard deviation weighted by the frequency of occurrence of a determined value centered in bins 0.05° wide.

Position	$\overline{\alpha}$	$\sigma_{\overline{\alpha}}$
1	−0.14°	0.19°
2	11.23°	0.11°
3	22.47°	0.21°
4	33.70°	0.18°
5	44.86°	0.14°
6	56.24°	0.22°
7	67.32°	0.21°
8	78.65°	0.13°

5.2. Relative accuracy of the position

Deviation angles, in linear approximation, inside which the control system reads the optical fibers signal have been measured. the overall angular dispersion is always under 1° (Tab. 1).

5.3. Spurious modulation

Multiple reflections inside a revolving mechanical support produce spurious modulation.

This effect has been tested detecting, with a Gunn diode, the signal emitted by a Gunn oscillator, coupled to a pyramidal waveguide, at 144 GHz with and without suitable shields which avoid, to the incoming radiation, to see any revolving part. The shields reduce the spurious modulation from a value of 11.4 % to 3.6 %, to this about 0.6 % of the change of the signal is due to temporal variation of the signal emitted by the Gunn oscillator (Fig. 2).

5.4. Outgassing of the optical fibers

The fibers Tyco Electronics 0-5349561-2 in vacuum environment don't outgas; inside a Helium leak detector in about five minutes an optical fiber (1 m long) reaches the same leakage rate present when nothing is inside the leak detector.

5.5. Thermal conductivity of the fibers

Thermal conductivity of the optical fibers between 4 and 300 K has been measured. In a test cryostat, where fiber specimens have been run between the base temperature and a controlled higher temperature, which has been measured together with the power required to heat the higher temperature side of the fibers. The conductivity of the support system and the radiative heat leak have been properly taken into account. The estimated conductive thermal load from 4 K to the first thermal shield of the cryostat, where they will be placed, carried by three pairs of fibers, 30 cm long, is 0.105 mW: not troublesome for our requirements.

6. Conclusions

The PILOT experiment for the first time will measure the interstellar dust polarization with unprecedent sensitivity thanks to its huge number of detectors. A detailed simulation of the performance of a HWP polarimeter has shown the necessity of cooling down the HWP and the polarizer. We have presented the PILOT polarization modulator, developed from the experimental requirements, all satisfied. At present new systems to improve the rotation of gears at low temperatures are being developing.

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